Measurement of peak power output and the lactate threshold: significance for endurance cycling performance

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Measurement of peak power output and the lactate threshold: significance for endurance cycling performance

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ABSTRACT

The lactate threshold (LT), onset of blood lactate accumulation (OBLA) and peak power output (PPO) are determined from an incremental cycling test to exhaustion. Typically, incremental exercise tests comprise stages of progressively increasing work intensity that very in length from 60 s to 10 min. However, little is understood about the impact that changing the length of stages during an incremental test has on the LT, OBLA and PPO. Whilst these physiological variables are routinely quantified in endurance athletes there is also little data establishing the relationship and metabolic significance of these variables to long or short duration endurance exercise tasks. This thesis comprises four experiments that examine the measurement of the LT, OBLA and PPO, but also the significance of these variables in endurance competitions of short or long duration.

The aim of the first experiment was to determine whether the LT and OBLA differed when measured from an incremental test comprising work stages of either 3 min or 8 min duration. Whereas one group of subjects recruited for the experiment was considered well trained ($\dot{V}O_2max$ > 60 $ml \cdot kg^{-1} \cdot min^{-1}$), the other group was less trained and considered recreational ($\dot{V}O_2max$ ~ 55 $ml \cdot kg^{-1} \cdot min^{-1}$). The data from this experiment demonstrated that the power output corresponding to the LT was significantly lower in the well trained (and not the recreational) subjects in the incremental exercise test comprising 8 min stages. At the same time, the OBLA (W) was significantly lower in the 8 min stage duration tests in both groups of subjects.

In the second experiment, the LT and OBLA together with the PPO were quantified in a group of well-trained cyclists completing two incremental test protocols. The first protocol involved 3 min stages with the second comprising stages of 5 min. The data from this experiment showed no significant differences in the LT, OBLA and PPO in the two incremental testing protocols. Therefore, an incremental test consisting of either 3 min or 5 min length stages could be used to determine the LT, OBLA and PPO in well-trained cyclists.

The aim of experiment three was to determine the relationship between PPO, the LT and OBLA as well as performance during a 20-min and 90 min cycling time trial (TT) in well trained athletes. The results showed that the power output corresponding to the LT and PPO was significantly correlated with average power output during the 90-min but not the 20-min time trial. Whilst, the LT and PPO represent two variables reflecting endurance performance in general, the results of this experiment also indicate that the duration of an endurance trial may influence the correlation between PPO, the LT and OBLA as well as the average power output during the endurance task.

The aim of the fourth study was to establish whether the LT could differentiate the metabolic responses in trained endurance athletes during a long (90-min) and short (20-min) endurance task. A group of well trained male cyclists were ranked in regards to the LT (% PPO) and assigned to one of two groups with either a 'high' or 'low' LT. The subjects performed two exercise trials of 20-min duration at 85% of PPO and also 90-min at 75% PPO. Physiological measurements were obtained during each of the trials and the responses compared between the two groups. However, the data indicated that there was no significant difference in the physiological responses of the two groups. Therefore, in trained subjects the LT is not a physiological variable that distinguishes the metabolic responses during set work endurance exercise of either 20-min or 90-min duration.

PUBLICATIONS ARISING FROM THIS THESIS

Referenced Journal Articles

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Bentley, D.J., McNaughton, L.R., Thompson, D., Vleck, V.E. and Batterham, A.M (2001). Peak power output, the lactate threshold and time trial performance in cyclists. *Medicine and Science in Sport and Exercise* 33(12): 2077-2081.

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DEDICATION

This thesis is dedicated to the memory of our mate Adam Wilton. I hope there is surf in heaven.

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LIST OF ABREVIATIONS

Adenosine Triphosphate	ATP
Anaerobic Threshold	AT
Analysis of Variance	ANOVA
Bicarbonate	HCO_3
Body Mass	BM
Carbon Dioxide Production	$\dot{V}CO_2$
Carbohydrate	CHO
Centimetre	cm
Exercise Test	EXT
Gram	g
Heart Rate	HR
Hours	hrs
Hour	hr
Hydrogen Ion	$[H^+]$
Kilogram	kg
Lactate Threshold	LT
Litre	L
Maximum Oxygen Uptake	$\dot{V}O_2max$
Minute	min
Microlitre	µL
Millilitre	ml
Millimolar	mM
Onset of Blood Lactate Accumulation	OBLA

LIST OF ABREVIATIONS (cont.)

Oxygen Uptake	$\dot{V}O_2$
Peak Power Output	PPO
Percent	%
Pulmonary Ventilation	$\dot{V}E$
Respiratory Exchange Ratio	RER
Revolutions Per Minute	rpm
Schroberer Rad Mebtechnik	SRM
Second	s
Time Trial	TT
Ventilation Threshold	VT
Watt	W

CHAPTER ONE

INTRODUCTION

CHAPTER ONE - INTRODUCTION

In Olympic and World Championship competitions there are a variety of activities that are designated as endurance sports. Some scientists feel that endurance sports are those which are completed in > 20 min (Hawley et al., 1997). It could be concluded from this suggestion, that there are many events differing by duration and intensity that could be defined as 'endurance'. Therefore, the physiological demands of these events, the physiological requirements of the competing athletes and the training preparations they use may vary dramatically in events characterised as 'endurance'.

Road cycling events are conducted on single days as in the World Cup circuit or as 'tour' events with a combination of many single 'stages' on separate days making up the overall competition such as the Tour de France. The stages in each tour may differ from courses of up 200-km in length to the individual time trial (TT) usually of 60-km in length. During Olympic competition there is a road race and a time trial completed on different days. Many other non-elite cycling TT events are completed usually over distances ranging from 16-km to 80-km and range in duration from 15 min to 2 hrs. Typically during time trials, the exercise intensity is relatively constant (Padilla et al., 2000) During longer road races the intensity may fluctuate quite markedly (Palmer et al., 1994).

The sport of triathlon involves sequential swimming, cycling and running over a variety of distances. The Ironman © event is composed of 3.8-km of swimming, 180-km of

cycling and a final marathon running stage (42.2-km). The World Ironman © Triathlon Championships are held each year in Hawaii. In contrast to the Ironman Triathlon, the 'standard' distance triathlon (formally known as the 'Olympic' distance triathlon) involves 1.5-km of swimming, 40-km of cycling and 10-km of running. The World Championships for this event are held in different locations each year with the leading competitors not usually specialising in both Ironman © and Standard distance events. The International Triathlon Union (ITU) also holds a series of races in the standard distance length each year to decide the World Cup champion. Within the sport of triathlon there are a number of factors that make this sport unique to other endurance sports such as cycling or running. The review article appearing in this thesis (following 'Literature Review') outlines the specific physiological aspects of triathlon.

During endurance events there are a number of physiological factors that will influence performance such as dehydration and substrate depletion (Kay and Marino, 2000). However, there are also key physiological parameters obtained from incremental exercise testing such as the lactate threshold (LT) and maximal oxygen uptake ($\dot{V}O_2max$) that are considered to be necessary requirements for athletes to perform in endurance events (Bassett and Howley, 2000). There has also been an interest in the maximum workload obtained during an incremental cycling ('peak power output') or running (peak treadmill velocity') exercise test as an indicator of endurance ability (Noakes et al., 1990; Hawley and Noakes, 1992). Incremental exercise testing is a standard procedure for obtaining $\dot{V}O_2max$ and the LT, together with the maximum workload. However, there are a number of protocols and procedures that are recommended by scientists to determine

these physiological parameters. Furthermore, triathlon and cycling events are conducted over different duration, which may result in different physiological demands for the athlete. The different physiological demands are relevant for specific training. At the same time, the contrast in physiological demand between different duration events may influence the validity of physiological variables obtained from incremental exercise testing in terms of correlation with performance.

The aims of the experiments outlined in this thesis were to examine the measurement procedures for determining the LT and maximum workload during incremental exercise testing. Furthermore, this work examined the physiological and performance significance of these two variables during endurance exercise of 'long' and 'short' duration.

The thesis is presented in eight separate chapters. The second chapter comprises a review of the literature concerning three areas related to the studies. These areas include the physiological variables related to endurance performance, as determined by incremental exercise testing, together with the affects of modifying the incremental exercise protocol on these variables. A second section reviews literature concerning the exercise intensity during endurance competitions. A third section examines exercise metabolism during endurance exercise. The General Methods (Chapter 3) describes in detail the experimental methods used within each of the four studies conducted.

Chapters 4 to 7 comprise the rationale, specific methods, results and discussion of results of the four studies completed. The first two studies examine the effects of manipulating

the incremental exercise protocol on the LT and maximum workload. The third experiment examines the relationship between the LT and PPO (in cycling) and endurance performance of long and short duration. A fourth and final experiment examines whether the LT could be used to distinguish the metabolic responses during long or short endurance exercise.

The last chapter of the thesis (Chapter 8) summarises the results of the four studies. Furthermore, a discussion of the main findings is presented together with potential future studies related to this work.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO - LITERATURE REVIEW

The following section of this thesis will review studies that have examined the relationship between physiological parameters and endurance performance. Studies examining the methodological factors influencing the physiological parameters associated with endurance performance will also be reviewed, as will research examining the relationship between the results of incremental exercise testing and endurance performance. Additional studies examining the exercise intensity during endurance competitions and exercise metabolism during endurance exercise will also be presented. Finally, the small amount of work examining the metabolic significance of the LT will be reviewed. The work presented focuses specifically on trained subjects. Where possible this review will consider sports involving cycle exercise such as road cycling, triathlon and mountain (off-road) cycling.

2.1 Incremental exercise testing and endurance athletes

2.1.1 Acute physiological adaptation to incremental exercise

In early studies on human subjects it was demonstrated that the concentration of lactate in the blood increased with exercise (Hill and Lupton, 1923). This was thought to be due to an inadequacy of O_2 supply to the working muscle (Hill et al., 1924). It was then subsequently recognised that lactic acid produced by the muscle was not due to hypoxia, and that it represented a valid indicator of the metabolic stress during exercise (Margaria et al., 1933). Whilst other pioneer exercise physiologists had developed the concept of

'maximal oxygen intake' (Hill, 1925), it was not until some time later that research concerning the significance of blood lactate accumulation during incremental exercise was conducted. This was primarily due to reasons concerning the acquisition of blood during exercise and the difficulties surrounding the analysis of firstly pyruvate, then lactate concentration (Hollman, 2001). With the refinement of associated technology, the procedure for collecting blood and measuring lactate concentration during incremental exercise has become a popular method for assessing the physiological capacity of an endurance athlete.

During low intensity exercise the blood lactate concentration (mM) remains minimal. However, as the exercise intensity is increased, a point is reached (which varies amongst individuals) where the lactate concentration abruptly rises and then continues to elevate with subsequent increases in exercise intensity (Myers and Ashley, 1997). The continued elevation of work rate and accompanying metabolic end products continues until the work rate can not be maintained i.e. fatigue eventuates. In conjunction with blood lactate accumulation, there is an increase in hydrogen ion concentration (H^+) which is responsible for the evolution of H_2CO_3 and CO_2 (Davis, 1985). The excess CO_2 contributes to the increase in pulmonary ventilation (VE) and breathing frequency (f_b) which is observed during heavy exercise when blood lactate accumulation is more pronounced (Davis, 1985). Therefore, during incremental exercise, in combination with blood lactate measurements, the expired volume and concentration of carbon dioxide (CO_2) and oxygen (O_2) can be used as a non-invasive measure of the dramatic increase in blood lactate accumulation. In the early 1960's that German researchers where able

demonstrate similarities between the curve of VE against time (and work rate) and both arterial lactate and pH levels during incremental exercise (Hollman, 1963). Despite these findings, there is still considerable debate as to whether the change in blood lactate concentration is coincident to an elevation in VE (Simon et al., 1986; Chicharro et al., 1997; Gaskill et al., 2001). However, it was established at the time that a point is reached where an abrupt increase in lactate production is also representative of an increase in respiratory parameters as well as the ratio of VE to CO_2 production ($\dot{V}CO_2$).

Based on the hypothesis that a dramatic increase in blood lactate is representative of an increase in 'anaerobic' metabolism, the concept of the 'anaerobic threshold' during incremental exercise was suggested as an increase in blood lactate accumulation and associated ventilatory responses was the 'transition' point from aerobic to anaerobic metabolism (Wasserman and McIlroy, 1964; Wasserman et al., 1973). This area of work, especially concerning the interaction of specific physiological adaptations during incremental exercise and the definition of set 'threshold' measurements has since been of major interest for exercise and respiratory physiologists for the last 30 years.

2.1.2 Identification of the physiological variables obtained in incremental exercise testing.

When an incremental exercise test is performed a number of physiological 'thresholds' can be established using blood lactate and expired gas measurements. The work or heart rate (HR) corresponding to set 'inflection points' can be determined (Coyle et al., 1983; Weltman et al., 1990) as well as other thresholds devised by mathematical modelling of

the blood lactate response to incremental exercise and recovery such as the individual anaerobic threshold or the Dmax threshold (Stegmann and Kindermann, 1982; Beaver et al., 1985; Cheng et al., 1992). Because of the many physiological parameters that can be quantified, as well as the inter-relationship of these variables, it is not surprising that considerable work has been conducted concerning the identification and definition of these variables.

The lactate threshold (LT) has been suggested as the exercise intensity *preceding* a one mM increase in blood lactate above baseline levels during incremental exercise (Coyle et al., 1983). In another study by Farrell et al., (1979) the LT was identified as the 'onset of plasma lactate accumulation' by examining the appearance of plasma lactate during incremental exercise. A later study defined the 'onset of blood lactate accumulation' (OBLA) as the work intensity that represented a lactate concentration in the blood of 4 mM. The OBLA was thought to be the point at which rapid accumulation of blood lactate occurred during incremental exercise (Sjodin and Jacobs, 1981). However, broadly speaking both typically represent a point during incremental exercise at any further increase in exercise intensity will result in excessive blood lactate accumulation and from thereafter continues to rise with subsequent increments until fatigue.

Typically the LT occurs around an absolute blood lactate concentration of ~2 mM (Simon et al., 1986; Hoogeveen and Schep, 1997). Other studies have reported the LT as being at a set lactate concentration of 2.5 mM (Allen et al., 1985; Hagberg and Coyle, 1983). The 'anaerobic threshold' (AT) has been defined as the workload during incremental exercise

that elicits a deflection from linearity in VE (Wasserman, 1987). The exercise intensity corresponding to 2 and 4 mM has also been proposed as the 'aerobic' and 'anaerobic' thresholds respectively (Aunola and Rusko, 1986; Robergs et al., 1990). Therefore, these variables have been suggested as important in terms of the coupling of ventilation parameters and the AT. In line with these observations it has also been suggested that the LT is coincident to the non-linear increase in VE or the AT (Davis et al., 1979). However, it has also been shown that this may depend on the training status of subjects and the LT may not be a point coincident to changes in VE and furthermore is not a point of absolute anaerobic metabolism (Simon et al., 1986; Chicharro et al., 1997). There is still ongoing debate concerning this issue which is very much confused by the definition of the physiological parameters and the methodology that is used to establish these parameters (Myers and Ashley, 1997). The existing research is also filled with a variety of categorisations of a shift in lactate kinetics during incremental exercise. Therefore the different physiological markers may provide different results in terms of the relationship to performance and sensitivity to endurance adaptation. Furthermore, the names and criteria of each variable make the literature confusing when comparing studies examining the 'lactate threshold' and endurance performance.

The LT has the advantage over other 'threshold' points representing 'fixed' blood lactate concentrations (i.e. 2 and 4 mM) because muscle lactate concentration and diffusion capacity can vary markedly between subjects (Tesch et al., 1982). A fixed lactate concentration may not truly reflect the metabolic stress occurring in muscle during incremental exercise due to the flux or metabolism of lactic acid. At the same time, other

data has indicated that the OBLA obtained from an incremental exercise test may not be as reliable as other measures such as the LT (Weltman et al., 1990; Grant et al., 2002). Other data suggests that the OBLA may be compromised by lack of excessive control of the training stress prior to an incremental test (Dolan et al., 1989). This data indicates that the LT maybe more reliable than the OBLA. This in turn may be significant in terms of training prescription and prediction of endurance performance.

One problem with determining the LT is establishing a 'baseline' level as well as an actual 'inflection point' (where the lactate concentration increases above baseline). Indeed, some authors suggest an inflection does not actually occur (Yeh et al., 1983). Therefore, it was proposed that mathematical modelling maybe better used to establish the LT point (Beaver et al., 1985).

The Dmax lactate threshold is determined by calculating the power output corresponding to the greatest perpendicular distance from a regression line of lactate to workload as well as a straight line formed by the first and last points of the regression line (Cheng et al., 1992). In contrast, the individual anaerobic threshold (IAT) is determined by quantifying the intersection (and corresponding workload) of two lines meeting on the lactate to workload curve during incremental exercise originating from points obtained at fatigue (plotted from lactate to workload) and following a 10 min recovery period (plotted from lactate to time) (Stegmann and Kindermann, 1982). Whilst the LT typically occurs at a lower exercise intensity and absolute blood lactate concentration (mM), other variables including the Dmax threshold (Cheng et al., 1992) and the individual anaerobic threshold

(IAT) which is established through lactate analysis during exercise and in the recovery stages following exercise (McLellan, 1985) have been identified. The work rate corresponding to the Dmax, the IAT and the OBLA have all been suggested as representative of the highest possible exercise intensity eliciting a steady state of exercise (Stegmann and Kindermann, 1982; Cheng et al., 1992). Therefore, these variables are important in terms of endurance training prescription. However, in terms of metabolic significance, the point at which lactate begins to accumulate (whether this be the LT or OBLA) is significant as it represents the work rate where changes in metabolic acidosis, ventilation characteristics change and shifts in substrate utilisation result in impaired muscle contraction and eventual fatigue (Myers and Ashley, 1997). This is in turn important for tracking changes in response to endurance training.

2.2 The lactate threshold (LT), onset of blood lactate accumulation (OBLA), peak power output (PPO) and endurance performance

The use of incremental exercise testing protocols to establish variables such as the OBLA and the LT together with the maximum workload [peak power output (PPO) in cycling] has become standard practice for scientists working with endurance athletes. The work rate or HR corresponding to the LT or OBLA can be used for training prescription or to establish the exercise intensity during endurance competitions (Sjodin et al., 1982; Mujika et al., 1995; Padilla et al., 2000). For example, in an early study on adaptation to endurance training Sjodin et al. (1982) quantified the velocity corresponding to the OBLA and found that adding one 20 min run at this intensity per week resulted in

improvements in running performance. In another study, Mujika et al. (1995) used the swimming velocity corresponding to the OBLA for the purposes of determining the training intensity of swimmers. Endurance activity is metabolically challenging for a human. It is known that during endurance competitions ranging from 10 to 70 min athletes will exercise in excess of 80% of $\dot{V}O_2max$ or 90% of maximum heart rate (HR_{max}) (Padilla et al., 2000). Other studies concerning cyclists have also quantified the competition intensity during road stages and time trial events by quantifying the HR corresponding to the OBLA and LT (Lucia et al., 1999; Padilla et al., 2000). The LT and OBLA have also been used to monitor the responses of the endurance athlete to training of varied volume and intensity (Steinacker et al., 1998; Verumlst et al., 1991; Pyne et al., 2001). For example, Vermulst et al., (1991) found that the power output at the OBLA was the variable that closely matched the changes in training load during a season in elite rowers. In a more recent study, Pyne et al., (2001) quantified the velocity corresponding to the LT during an incremental test in conjunction with field performance to quantify the training induced responses in elite swimmers. Therefore, the LT and OBLA represent two variables that are commonly used by exercise physiologists working with endurance athletes in a training and competition setting. However, the most popular procedure concerning the LT and OBLA in endurance sports have been the relationship between these variables and endurance performance (Farrell et al., 1979; Zhou et al., 1997; Bishop et al., 1998b; Bishop et al., 2000). Other studies have shown that the PPO, in conjunction with $\dot{V}O_2max$ and the LT, obtained in an incremental cycle test, or peak running velocity, in an incremental running test have been shown to correlate with endurance performance (Noakes, 1990; Hawley and Noakes, 1992).

2.2.1 The relationship between the LT, OBLA and endurance performance

Coyle (1995) has suggested that an elevated $\dot{V}O_2$max in conjunction with an elevated LT will to a large extent dictate endurance performance. Indeed, other authors have also conveyed similar attitudes regarding the LT and $\dot{V}O_2$max (Pate and Branch, 1992; Bassett and Howley, 2000). Also, within the coaching community it is widely acknowledged that heightened endurance performance is associated with a high LT expressed as a % of $\dot{V}O_2$max. Whilst there are other biomechanical and psychological restraints limiting endurance performance, Coyle (1995) further suggests that 'performance velocity' (the average speed in an endurance event) will be dictated by the 'performance power' (the average work performed during an endurance task) and 'performance $\dot{V}O_2$' which is in turn influenced by the % $\dot{V}O_2$ at the LT as well as $\dot{V}O_2$max.

Whilst these models suggest that the LT is indicative of endurance performance, many research groups have attempted to correlate or predict endurance performance using the LT and OBLA (Farrell et al., 1979; Zhou et al., 1997; Bishop et al., 1998b; Bishop et al., 2000). However, much of the work examining the physiological parameters associated with endurance performance is not comparable due to the different methodological approaches used by researchers in this area. The studies so far have varied due to differences in subject ability level and gender, by the mode of exercise or the distance

that is used as the endurance task. At the same time, other studies are conducted in a field setting or within a laboratory.

The pioneering exercise physiologists were primarily interested in the maximum level of 'O_2 intake' during incremental exercise in relatively untrained subjects (Hill et al., 1924). Other researchers were quick to identify that trained endurance athletes had a greater capacity to use O_2 during incremental exercise and therefore possessed a higher maximal O_2 intake than more sedentary counterparts (Robinson et al., 1937). Indeed, Costill et al. (1973) presented a strong correlation coefficient (r=-0.91) between $\dot{V}O_2max$ and 10 mile running time. However, in this study the $\dot{V}O_2max$ of the subject population varied quite dramatically. Bassett and Howley (2000) were to later comment that if one were to narrow the range of values the relationship would be reduced. However, other studies have indicated the variation in endurance running performance were not explained by the $\dot{V}O_2max$ in well trained subjects homogeneous in terms of $\dot{V}O_2max$ (i.e. well trained or elite populations) (Bassett and Howley, 1997). Other more recent investigations in well-trained triathletes have suggested that $\dot{V}O_2max$ is not a good predictor of either 40-km cycle or 8-km running performance (Zhou, et al., 1997). Studies using elite cyclists have demonstrated that $\dot{V}O_2max$ does not differentiate performance in professional and very well trained amateur cyclists (Lucia et al., 1998). Therefore, whilst $\dot{V}O_2max$ can be viewed as an integral component to submaximal endurance performance (Coyle, 1995; Bassett and Howley, 2000), studies with highly trained subjects indicate that $\dot{V}O_2max$ may not serve as the best indicator or predictor of endurance performance. For the

significance of submaximal physiological parameters (i.e. the LT) to be fully examined, the subject population being assessed must be homogeneous in terms of $\dot{V}O_2$max.

The exercise intensity corresponding to set blood lactate concentrations (i.e. 2 and 4 mM) or inflection points (the LT) obtained 'submaximally' during incremental exercise tests have been suggested to be better indicators than $\dot{V}O_2$max of endurance performance when the population being assessed is well trained (Coyle et al., 1988; Coyle et al., 1991). Farrell et al. (1979) found that the onset of plasma lactate accumulation was correlated to endurance running performance in distances ranging from 10-km up to the Marathon. However, this study included athletes whose ability level and $\dot{V}O_2$max varied quite dramatically. Other studies have also demonstrated significant correlations between the $\dot{V}O_2$ or workload corresponding to the LT or OBLA and endurance performance in populations that were of very mixed ability level (Bentley et al., 1998; Bishop et al., 1998b; Bishop et al., 2000). For example, in two recent investigations (Bishop et al., 1998b; Bishop et al., 2000), it was established that the Dmax lactate threshold and the OBLA were the two variables that were most related to the average power output achieved during 60 min of cycle exercise in female cyclists. However, as in other studies these authors used a population of female cyclists of mixed ability level ($\dot{V}O_2$max Range 35.5 – 57.9 $ml \cdot kg^{-1} \cdot min^{-1}$). Other studies have presented similar findings in groups of female or mixed gender groups (Nichol et al., 1997; Bishop et al., 1998b; Bishop et al., 2000; Wiswell et al., 2000). Furthermore, there are studies that have examined the LT and endurance performance in older population groups (Nichol et al., 1997; Wiswell et

al., 2000). Therefore, although a correlation was shown for the LT or OBLA and endurance performance is unclear as to the effect that the variation in $\dot{V}O_2max$ or different would have on this relationship. In two studies, it has been shown that although these studies demonstrate that submaximal thresholds or inflection points correlated well with endurance performance, the subject population examined was mostly homogeneous in terms of endurance ability and $\dot{V}O_2max$.

In road cycling events, time trials (TT) are held over distances of 10-km to 60-km. In the sport of triathlon, the cycle stage is completed over courses ranging from 20-km to 180-km. Middle and long distance running, modern pentathlon and rowing events also differ in regards to event duration. The metabolic demands of such events may differ markedly in terms of oxygen demand and substrate metabolism (Romijn et al., 1993; Padilla et al., 2000). This in turn may effect the relationship between the selected physiological parameter and performance. However, there is relatively little information concerning the relationship between the LT, OBLA and endurance performance of varied duration in well-trained subjects.

In one study it was shown that the (anaerobic) ventilation threshold, determined as a non-invasive method of establishing the LT, was correlated to the time taken to complete a 16.1-km time trial (Loftin and Warren, 1994). However, this work was conducted within a laboratory setting. Similarly, two other studies have demonstrated that the ventilation threshold is the single best variable for prediction of cycle time performance in the field of distance ranging from 15-40 km (Miller and Manfredi (1987; Hopkins and McKenzie,

1994). Therefore, from this data it seems that the ventilation threshold (which is typically related to the LT) is a good indicator of endurance ability in field and laboratory situations in moderately trained cyclists. However, other researchers have presented very weak correlations between the work rate corresponding to blood lactate concentrations of 2 and 4 mM and the time taken to complete a field cycling or running time trial (Lehmann et al., 1983; Hoogeveen and Schep, 1997). In a recent study concerning rowers it was shown that $\dot{V}O_2$max was the single best predictor of rowing performance over a duration of 6-7 min (Cosgrove et al., 1999). In another study it was shown that the 'anaerobic threshold' calculated from expired volumes of CO_2 and O_2 was not related to 90 or 180-km cycling performance in a triathlon race (Whyte et al., 2000). Thus, it is possible that the relationship between the LT or other physiological variables associated with the LT, and endurance performance may change depending upon the length of the performance trial completed but also the mode of activity that is completed. Indeed, the data by Hoogeveen and Schep (1997) and Lehman et al., (1983) indicate that correlating performance with the workload corresponding to fixed blood lactate concentrations may not be that informative. This in part maybe due to the suggestion by Coyle (1995) that the workload corresponding to the OBLA is not a true reflection of the metabolic stress that is occurring at that work rate due to changes in blood lactate kinetics. At the same time, most investigations have examined cycling performance over a duration of less than 60 min (Coyle et al., 1991; Bishop et al., 1998b). No studies have systematically examined the relationship between the LT and the OBLA in trained cyclists performing 'short' (<60 min) or 'long' (>60 min) endurance tasks.

The studies conducted so far have examined subjects performing a TT either outdoors (Hoogeveen and Schep, 1997; Nichols et al., 1997; Bentley et al., 1998) or within a laboratory setting where performance is quantified by the elapsed time or the average power output during the trial (Loftin and Warren, 1994; Bishop et al., 1998b; Bishop et al., 2000). There are a number of factors that my influence cycling time trial performance in the field such as biomechanical or anthropometrical restraints (Swain, 1990). Indeed, Balmer et al. (2000a) have recently shown that the PPO obtained during an incremental exercise test (using 60-s stage duration) was highly correlated to the average power (measured using an SRM crank system) in a 16.1-km time trial, but this correlation was not evident when performance time (min) was considered. Therefore, other factors influencing the 'performance velocity' outside of the 'performance power' (Coyle, 1995) may affect the relationship between the physiological parameters and endurance performance. Performance trials are often conducted in the laboratory in conjunction with incremental exercise testing (Jeukendrup et al., 1996; Burke et al., 2000). The advantage of performing a TT in a laboratory setting is that it eliminates other restraints other than the physiological (and psychological) capacity of the subject being assessed. That aside, it is possible that the correlation between cycling performance and the LT maybe weakened due to other factors aside from any physiological constraints. Despite this, there are at present, no data examining the relationship between the LT, OBLA and cycling performance over short and longer duration (i.e. less than 30 min or greater than 60 min) in well-trained specialist TT cyclists and triathletes of similar ability level.

2.2.2 The PPO and endurance performance

Administering an increase in work rate during incremental exercise has long been used as a method to induce $\dot{V}O_2max$ (Taylor et al., 1955). However, the maximum work rate or workload obtained during an incremental exercise test has become popular as an endurance performance indicator in running and cycling (Noakes, 1990; Hawley and Noakes, 1992; Balmer et al., 2000b). It is also now popular to use this variable to prescribe high intensity endurance training (interval) sessions (Hawley and Stepto, 2001).

The maximum work rate is obtained by measuring the highest fully completed work rate for a pre-determined period during an incremental test (Hawley and Noakes, 1992). This ranges between 60-s or 4 min duration (Noakes, 1990; Padilla et al., 2000). If a single workload is not completed equations can be used to establish the maximum workload that consider the fraction of the workload stage where fatigue occurred (Hawley and Noakes, 1992; Kuipers et al., 1985). There are a variety of definitions of the maximum workload including 'peak power output' (PPO) or 'workload max (Wmax)' in cycling or 'peak treadmill velocity' in running (Noakes, 1990; Hawley and Noakes, 1992; Balmer et al., 2000b). The former definition should not be confused with the peak power obtained during short 'all-out' tests of anaerobic power (Paton and Hopkins, 2001). Of practical significance the PPO has been shown to correlate with $\dot{V}O_2max$ (Hawley and Noakes, 1992). Therefore, this variable can be used to predict $\dot{V}O_2max$ without equipment for gas analysis.

In an initial study concerning the relationship of this variable to endurance performance, Noakes et al. (1990) found that the peak treadmill running velocity obtained from an

incremental exercise tests using stages of 2.5 min duration was correlated (r=-0.91 to r=-0.94) to endurance performance between 10 km and the Marathon. Another study reported an r^2 value of 0.94 between the average running speed during a 5-km running trial and the peak treadmill running velocity obtained from an incremental test using stages of 30-s duration. Hawley and Noakes (1992) then Bentley et al. (1998) were to present data demonstrating a significant correlation between PPO and field cycling time trial performance between 20 and 40-km. More recently, Balmer et al. (2000a) found a significant correlation between PPO and the average power generated during a 16.1 km cycling time trial.

A common methodological contrast in all the studies has been the length of stages during the incremental test used to determine the PPO. For example Bentley et al. (1998) used a PPO averaged over 3 min duration. In contrast, Hawley and Noakes (1990) have used a 2.5 min average value. Furthermore, Balmer et al. (2000b) use an incremental exercise test of 60-s stages to determine PPO. However, no clear rational is given as to why the duration of the PPO is selected. The reliability of PPO during incremental exercise test of stages 60-s duration has only recently been reported (Balmer et al. 2000b). However, the effect of modifying the length of stages on the PPO value has not yet been investigated. Therefore the data concerning the reliability and validity of PPO measured over different duration is lacking.

2.2.3 The effects of manipulating the incremental exercise protocol on the physiological parameters associated with endurance performance.

The results of incremental exercise testing is used to quantify changes in performance, to correlate with performance and to establish the exercise intensity in endurance training and competition (Sjodin et al., 1982; Mujika et al., 1995; Padilla et al., 2000). The physiologist can approach incremental exercise testing with a variety of protocols aimed at determining a number of different physiological variables. However, modification of the exercise testing protocol can have implications for the variables measured and hence the use of these variables in longitudinal analysis and performance diagnostics. The maximum workload (PPO in cycling) can also be established as the highest work rate completed for a designated period (i.e. 60-s to 4 min) (Balmer et al., 2000b; Padilla et al., 2000). Therefore, whilst the PPO has been established as a variable sensitive to longitudinal change, this variable may change on the basis of the exercise protocol that is completed.

During incremental exercise testing the protocol can be manipulated in a number of different ways to establish the desired physiological adaptation. It is common for the duration (min) of each stage of the test as well as the size of the work increment to be modified during incremental exercise (Coyle, 1995; Hansen et al.,1988). Depending upon the exercise mode, the increase in work rate may consist of either an elevation in velocity (m·s) or gradient (%) during treadmill tests or power output (W) during cycle exercise. By reducing the length of stages or increasing the magnitude of the work rate, the total duration of the test is reduced because the subject is brought to exhaustion much sooner.

The incremental exercise test may also involve a continuous or discontinuous protocol with rest periods between each stage. During submaximal exercise of the same relative intensity, the metabolic response may differ depending upon the training status of the subject being assessed (Baldwin et al., 2000). Therefore, the metabolic response to incremental exercise of differing stage duration may change between subjects of different training status. The training status of subjects coupled to the design of the incremental exercise protocol may also influence the submaximal exercise response, which may impact the physiological variable (s) that are being determined. In terms of blood lactate measurements, the type of blood medium (venous, arterial, mixed arterio-venous) that is obtained may also influence the concentration of this metabolite due to the overall diffusion of lactate into the blood. (Foxdal et al., 1996; Yoshida, 1984; Smith et al., 1997).

There are a number of studies comparing the results of incremental exercise tests of differing protocol. However, nearly all of these investigations have been in untrained subjects. Earlier studies sought to establish a testing procedure useful in assessing either physical fitness or central cardiovascular function (i.e. $\dot{V}O_2max$) in untrained populations whilst limiting patient discomfort during intensive exercise (Balke and Ware, 1959; Bruce et al., 1963; Taylor et al., 1955). These exercise protocols consisted of treadmill exercise that involved increments of both speed (miles·hr) and gradient. Each test was named after the principle researcher involved with the Bruce protocol involving 3 min continuous stages and the Balke test 60-s stages. The 'Taylor' protocol involved 'interrupted' or discontinuous work bouts of 3 min duration on consecutive days and was

used to establish maximal aerobic power ($\dot{V}O_2max$) (Taylor et al., 1955). The justification for using this test was that the interrupted work bouts would eliminate subject discomfort during near maximal exercise. Indeed Taylor et al. (1955) reported that $\dot{V}O_2max$ was highly reproducible using this protocol. To rectify this problem, Mitchell et al. (1958) compared the protocols that had previously been used with one that comprised short breaks between each exercise bout. These authors presented data confirming that oxygen uptake ($\dot{V}O_2$) parameters can be accurately determined using the same exercise protocol as that of Taylor et al. (1955) with only 10 min separating each work rate increment. Other researchers were to use similar exercise protocols to quantify the LT in trained and untrained subjects (Farrell et al., 1979; Coyle et al., 1983). However, a protocol of this type is considered time consuming especially for athletes in full time training.

Froelicher et al. (1974) later compared $\dot{V}O_2max$ measured during incremental exercise using the protocols suggested by the Balke, Bruce and Taylor research groups (Balke and Ware, 1959; Bruce et al., 1963; Taylor et al., 1955). It was demonstrated that the Taylor protocol (Taylor et al., 1955) resulted in a higher $\dot{V}O_2max$ value. However, in this study the stage duration and work increments were of differing magnitude and therefore it is difficult to compare the maximal values (i.e. $\dot{V}O_2max$) obtained from these protocols. Furthermore, the subjects were untrained and not accustomed to intensive exercise. Thus the possibility remained that exercise protocols involving longer stage duration (> 3 min) may influence maximal results. Subsequent studies conducted firstly by Whipp et al.

(1981) and then Buchfuhrer et al. (1983) demonstrated that a shorter exercise protocol involving work rate increments every 60-s resulted in a higher $\dot{V}O_2max$ level. Buchfuhrer et al. (1983) for example measured $\dot{V}O_2max$ obtained from protocols involving increments of either 15, 30 or 60 $W \cdot min^{-1}$ until exhaustion. These researchers demonstrated that $\dot{V}O_2max$ was highest when the exercise test duration was within 8-17 min and involved increments of 30 W every 60-s. They concluded the reduction in $\dot{V}O_2max$ with longer protocols was due to an increase in body temperature, dehydration, modified substrate utilisation and general discomfort experienced by the subjects. Buchfuhrer et al. (1983) was also able to demonstrate the $\dot{V}O_2$ at the AT was similar with the different test designs. These results were subsequently replicated by McLellan (1985) who compared the LT and ventilation thresholds (VT) using a cycle ergometer protocol of 1, 3 or 5 min stages with 30 W increments between stages. However, in another study Yoshida (1984), found that although the maximum work rate and $\dot{V}O_2max$ obtained was lower in an incremental exercise test comprising 4 min compared with 60-s length stages, the $\dot{V}O_2$ at the AT and the (4 mM) OBLA were similar between tests. In all of these studies the subject population was both untrained and heterogeneous in terms of maximal functional capacity, therefore the variation in physical fitness and the ability to tolerate heavy exercise for durations > 3 min may have lead to the confounding results in terms of $\dot{V}O_2max$ or the LT. At the same time, whilst the maximum workload (ranging from 60-s to 5 min) obtained during an incremental test is now considered a valid indicator of endurance performance, the studies previously completed did not report this variable. At

the same time, the possibility of a lower $\dot{V}O_2$max value during incremental exercise tests of longer duration may impact on submaximal results such as the OBLA and LT expressed as a % of $\dot{V}O_2$max. Therefore, it has not been fully established what effected modification of the exercise protocol has on PPO and in turn what affect this has on the relationship of this variable to endurance performance or the sensitivity of this variable to long term endurance training in athletic populations.

In terms of the blood lactate response to incremental exercise it has been suggested that it is necessary to use stage lengths of 3-6 min during incremental exercise to obtain precise lactate measures to determine the desired metabolic inflection points (Thoden, 1991). Most exercise protocols had been designed to minimise intolerance experienced by untrained subjects in order to obtain a valid measure of aerobic capacity and cardiac function. However, the existing research in untrained subjects suggested that using exercise protocols incorporating stages of > 3 min may compromise the obtained $\dot{V}O_2$max value. Furthermore, protocols involving stages of > 3 min increase the length of the test. At the same time, the maximum workload or peak power output in cycling achieved may also decrease because of the prolonged stage length and overall length of the test. The relevance of these factors and the relationship between peak power output and endurance performance has not been investigated.

Yoshida (1984) extended previous findings by examining the blood lactate response to two incremental exercise tests comprising 25 W increments every 60-s or 4 min. The

results demonstrated that the workload but not the $\dot{V}O_2$ at the OBLA and lactate threshold (LT) was significantly higher in the 60-s stage test compared to the 4 min stage protocol. Another two studies have presented data that either supports (Kim et al., 1988) or shows no significant differences in the LT or OBLA using incremental exercise tests comprising stages of 1 min to 5 min duration (McLellan, 1985). Yoshida (1984) was able to obtain coupled arterial and venous blood samples and explain that the elevated LT and OBLA workload that was calculated in the 60-s stage test was due to a delayed appearance of lactate in venous as opposed to arterial blood. Indeed, other studies have shown the individual anaerobic threshold (IAT) which is quantified using the lactate response to a recovery period following maximal exercise can be influenced by the length of stages during an incremental exercise test (Coen et al., 2001; McLellan, 1985). More recently Smith et al. (1997) showed no differences in the plasma or whole blood LT using visually or mathematically modelled LT inflection points, with an incremental exercise test comprising either 60-s or 4 min stage durations. Therefore, it is possible that the blood medium (arterial vs. venous) obtained for blood lactate measurements during incremental exercise in combination with longer stage durations may influence the LT and especially the OBLA when this is thought to be the point of a heightened elevation in blood lactate accumulation. As opposed to passive diffusion, it is now known that diffusion of lactate into the blood occurs via a protein transport system (Bonen et al., 1997). Exercise training is known to enhance the expression of these transporters in muscle (Pilegaard et al., 1994). Therefore, the capacity if lactate dissipation in combination with the length of stages during an incremental test may influence the appearance of lactate in the blood and subsequent determination of the exercise intensity

corresponding to the LT or OBLA . However, the affect that a difference in lactate dissipation during incremental exercise comprising different length stages has not been investigated in trained compared with untrained subjects.

The studies that had been conducted examining the influence of different exercise protocols and the metabolic results obtained from these protocols had been conducted in untrained subjects. During cycle exercise it has been reported that well trained subjects are able to exert more efficient force during the down phase of the pedalling cycle (Coyle et al., 1991). Thus, during prolonged submaximal exercise of the same relative exercise intensity, the recruitment patterns of slow and fast motor units and subsequent lactate production may differ between cyclists of varying ability level. Indeed it has been suggested that changes in motor recruitment patterns may influence changes in lactate during prolonged cycle exercise (Marcinik et al., 1991). Thus, a combination of cycling ability level and exercise protocol coupled with lactate dissipation capacity may influence subsequent LT and associated measurements during different incremental exercise tests.

Traditionally the 'model' endurance athlete possesses an elevated $\dot{V}O_2max$ and a LT inflection point that occurs as close as possible to $\dot{V}O_2max$ (Coyle, 1995). Therefore the physiological assessment of the endurance athlete should include capacity to accurately measure these variables. In the studies conducted using trained and untrained populations, a shorter exercise protocol involving short (~ 60-s) stage increments is typically used to measure $\dot{V}O_2max$, then on a second day a submaximal test is used to quantify the LT and related variables (Coyle et al., 1983; Coyle, 1995). In comparison, it is also popular to use

a single test comprising stage duration of > 3 min to assess trained subjects (Bishop et al., 1998b; Bentley et al., 1998; Padilla et al., 2000). At the same time, other scientists working with elite cyclists recommend using an incremental test comprising 60-s stage increments to determine the LT (Lucia et al., 1998). However, this form of test may overestimate the workload obtained at the LT (Smith et al., 1997). In the other extreme, a longer test may result in a lower $\dot{V}O_2max$ in combination with a higher LT point (Yoshida, 1984; Kim et al., 1988). No research has compared $\dot{V}O_2max$, the maximum workload and the LT obtained from a shorter stage test with a longer test in a trained population more resistant to exercise stress-induced fatigue and discomfort.

Two recent studies have examined whether incremental exercise tests comprising stages of > 3 min duration would result in a lower $\dot{V}O_2max$ in trained cyclists and rowers (Bishop et al., 1998a; Pierce et al., 1999). Pierce et al. (1999), compared four incremental rowing tests using stage durations of either 60-s, 3, 4 or 5 min duration. The results showed that $\dot{V}O_2max$ was not different between the 60-s, 3 and 4 min staged tests. However, the $\dot{V}O_2max$ obtained from the 5 min stage test was significantly lower. At the same time, the respiratory exchange ratio (RER) was significantly higher in the 60-s stage test as opposed to the remaining incremental exercise tests. Similarly, Bishop et al. (1998a) found that $\dot{V}O_2max$ was not different between two incremental exercise tests comprising stage increments of 60-s (25 W) and 3 min (10 W) duration. Whilst these studies seem to indicate that incremental exercise tests comprising stages of < 3 min duration do not affect $\dot{V}O_2max$, in both studies lactate measurements where not obtained.

Therefore, it can not be established whether the LT or OBLA together with the workload or $\dot{V}O_2$ at set lactate inflection points differed between test comprising stages of 60-s, 3 or 5 min duration. Furthermore, the maximum workload was not quantified. Therefore, the affect of the different incremental exercise protocol has on PPO obtained from an incremental exercise test and the relationship of this variable to $\dot{V}O_2$max has not been established.

Other research investigations have compared the LT and OBLA coupled with other metabolic thresholds from incremental exercise tests comprising short or longer stage durations in trained and untrained subjects (Foxdal et al., 1994; Foxdal et al., 1996; Weltman et al., 1990). Weltman et al. (1990) compared the $\dot{V}O_2$, velocity and HR at the LT and fixed blood lactate concentration of 2, 2.5 and 4 mM obtained from two incremental exercise tests comprising discontinuous stages of 10 min duration or continuous 3 min stages. They found that in a group of relatively well trained runners the LT did not differ between tests. However, the $\dot{V}O_2$ and velocity at a set blood lactate concentration of 2 mM was significantly higher in the 10 min discontinuous test. In contrast Foxdal et al. (1996), concluded that exercise tests using stages of 4 to 6 min duration do not result in steady state blood lactate concentrations. Furthermore, these authors suggested that in determining the OBLA threshold in trained subjects stages of 8 min duration should be used. It is likely that modification of the incremental exercise test protocol will influence the LT and OBLA as well as the peak $\dot{V}O_2$. There is no data that have examined the relationship between variables obtained from a short or longer

incremental exercise test and endurance performance such as the average power obtained during a time trial. At the same time, the data presented by Weltman et al. (1990) was reported in absolute terms. There are no studies that have compared the results (i.e. the LT or OBLA) obtained from an incremental exercise test using either 3 min stages or a longer stage duration relative to $\dot{V}O_2$max that is obtained from the 3 min incremental test or that obtained from a shorter style test where $\dot{V}O_2$max is likely to be higher.

Protein transporters facilitate most lactate transport from the muscle cell (Bonen et al., 1997). Yoshida (1984) has also shown that the kinetics of lactate diffusion may confound blood lactate results during incremental exercise. Thus the diffusion capacity of lactate and the time allowed for this diffusion to occur before an increment in work rate may influence the blood lactate response to exercise. Therefore the results of many studies may be compromised by the choice of blood sample and possible differences in blood lactate diffusion rates. Other studies conducted by Swedish researchers (Foxdal et al., 1994) have also shown that the choice of blood to measure lactate concentration combined with more lengthy protocols (stages of >8 min) resulted in different results. In a recent study it has been shown that as opposed to a LT inflection point, the $\dot{V}O_2$ at a set lactate concentration of 2 mM may be significantly underestimated when using plasma lactate concentrations (Smith et al., 1997). In another study, Weltman et al. (1990) used whole blood and compared the workload at a 2 mM lactate concentration during two different incremental exercise protocols comprising either 3 min or 10 min stage durations. These authors found that the workload at the 2 mM point was significantly

lower in the 10 min stage test. Thus, at a set lactate concentration the $\dot{V}O_2$ or workload may be lower, which has implications for athlete assessment. On the basis of these studies, it also seems likely that in order to obtain a reliable measure of metabolic stress (as determined from venous blood lactate measurements) longer exercise protocols are needed to allow lactate diffusion before an increment in work occurs. However, this in turn may compromise the $\dot{V}O_2$max and maximum workload measurements. At the same time, conducting two tests on separate days is considered too time consuming for athletic populations. Furthermore, trained subjects have a greater capacity for lactate dissipation from skeletal muscle (Pilegaard et al., 1994). It is not clear what effect these biochemical characteristics have on the lactate results of different incremental exercise in trained and untrained subjects.

It is typical for researchers to use the LT, OBLA or AT to predict endurance performance (Bishop et al., 1998b; Farrell et al., 1979; Zhou, et al., 1997). It is possible that the changes in these variables with the different exercise protocols may be significant in terms of training assessment or performance prediction. However no investigators have compared the LT, OBLA and AT obtained from different exercise tests comprising short or longer duration stages and the sensitivity of these measures to training adaptation or the correlation of these variables to endurance performance.

2.3 Physiological demands of the endurance competition

2.3.1 Measurement of exercise intensity during endurance competition

The exercise intensity during endurance competition is not easy to establish due to the methodological difficulties involved with this procedure. The information to date in this area is limited by the devices used to quantify the exercise intensity. The most common method is to measure heart rate (HR) with portable telemetry monitors during the actual competition and extrapolate these results to physiological parameters such as the HR at the 'anaerobic' ventilation (VT) or lactate threshold (LT) obtained from an incremental exercise test (Palmer et al., 1994; Lucia et al., 1998; Padilla et al., 2000). In these instances, the average HR can be expressed relative to the HR corresponding to a set submaximal physiological variable (i.e. the LT or OBLA) or to HRmax. (Lucia et al., 1998; Padilla et al., 2000). Whilst this procedure provides useful information to the coach and athlete, it is limited by the effects of dehydration and subsequent cardiac drift as well as environmental heat stress (Gilman, 1996). Therefore, the HR during an endurance competition may not accurately reflect either the metabolic demands of the event or the perception of effort. In running activity, the average velocity (kph or $m \cdot s^{-1}$), together with HR, during an event can be quantified and again this variable can be compared to the results of an incremental exercise test (Potteiger and Evans, 1995).

More recently, portable gas analysis systems such as the Cosmed K4, B^2 (Italy) have been developed and validated (Hausswirth et al., 1997). Thus, other metabolic variables such as oxygen uptake ($\dot{V}O_2$) and the Respiratory Exchange Ratio (RER) can be measured during actual field competition. Therefore, aside from the constraints of the equipment in a competition setting, the metabolic cost of the activity can be accurately quantified. Coupled with the portable telemetry systems for measurement of HR and gas

analysis, a number of devices have also been developed so that the external mechanical power (W) can be determined during field cycling trials (Jones and Passfield, 1998).

Laboratory based trials in cycling and running are commonly used to simulate endurance competition (O'Brien et al., 1993; Schabort et al. 1998). In these instances, the metabolic response to the exercise trial can be accurately measured without any environmental constraint. However, the limitation in studies incorporating this kind of methodology is that it is not actually a true competition. Therefore, the subject may not be entirely motivated to perform their 'best effort' for the task. At the same time, whilst the 'performance power' can be determined in these instances, the 'performance velocity' maybe inflated because it is not performed in the field where other factors such as aerodynamics and morphology may influence the speed of the effort (Swain, 1990; Kyle, 1994).

2.3.2 The exercise intensity during endurance cycling and triathlon competitions

The critical power concept states that as the exercise duration increases, the intensity of exercise (% $\dot{V}O_2$max or HR_{max}) will decrease (Walsh, 2000). In terms of critical power, the research indicates the longer the endurance competition the lower the exercise intensity and work rate that can be sustained during this task (Lucia et al., 1998; Davison et al., 1999; Padilla et al., 2000). For instance, Lucia et al. (1998) quantified the exercise intensity of eight professional athletes during the Tour de France cycling race using a protocol of continuous HR monitoring. At the completion of the event an incremental exercise test was performed to determine the ventilation threshold (VT) with three

exercise intensities established (during the competition) on the basis of the VT. The results showed that 70% of the time, exercise was performed below the first ('aerobic') ventilation threshold (VT_1) whereas approximately 20% were spent between VT_1 and VT_2 ('anaerobic threshold') and 10% above VT_2. Cycling stage races are conducted over varying terrain and different disciplines such as team and individual time trials, mountain and flat stages. The results also indicated that during time trials most of the time (90%) the exercise intensity was well above the VT_2 or > 87.5 ± 3% of $\dot{V}O_2max$. Therefore, time trial events of duration ~ 60 min are performed at an exercise intensity of > 80% $\dot{V}O_2max$. However, there are limited data examining the exercise intensity of endurance events in cycling and triathlon of > 60 min in duration.

In another study, Padilla et al. (2000) compared the exercise intensity during short and long cycle time trials of duration ~ 40 min and ~ 70 min respectively. These workers found that in professional cyclists ~ 50% of the exercise time during the short trials was spent at or above the OBLA but well above the LT. In contrast, and because of the increase in duration, the exercise time was nearly always below the OBLA with ~ 60% of the exercise time spent at or above the LT. This intensity represented ~ 84% and 79% of HR_{max} for the short and long trials respectively. Other studies show that cycling time trials of duration up to 90 min are completed at an intensity of between 75 and 85% of the maximum workload obtained during an incremental exercise tests (Davison et al., 1999). Therefore, the longer the duration the lower the exercise intensity sustained during the trial. This in turn may influence the metabolic responses and fatigue manifestation occurring in the trial completed.

Triathlon involves sequential swimming, cycling and running. Recently, a French research group has staged simulated sprint (0.75-km swim, 20-km cycle, 5-km run) triathlon competitions in elite athletes (Hausswirth et al., 1999; Hausswirth et al., 2001). Typically the duration of the cycling and running in these events is ~ 40 min. These researchers used a portable gas analysis system (Cosmed, K4, B^2) to quantify the exercise intensity during the competition. Hausswirth et al. (1999) for example found that elite triathletes were able to exercise in excess of 90% of $\dot{V}O_2max$ for 30 min during the cycling segment with a similar exercise intensity during the running portion (~17 min).

Overall the data from the last 5 yrs indicates that depending upon the race distance, elite athletes are able to exercise at > 80% $\dot{V}O_2max$ in typical time trial competitions lasting between 20 and 70 min in duration (Padilla et al., 2000; Hausswirth et al., 1999). However, the mode of exercise together with the specific demands of the task may influence this intensity (Schabort et al., 1998; Arkinstall et al., 2001). Typically, the physiological attributes measured in incremental exercise tests in elite athletes are far superior to even well-trained athletes (Mujika and Padilla, 2001). Thus, despite standard 'threshold' or 'inflection' points (obtained from incremental exercise) occurring at a similar relative (%) exercise intensity in more sedentary populations, the absolute workload at these thresholds in elite athletes is much higher. At the same time, the absolute work rate and energy expenditure maybe far superior in elite athletes (Jeukendrup et al. 2000) Therefore, the absolute exercise intensity or performance power during competition is much greater in these athletes.

2.4 Substrate metabolism during endurance exercise

2.4.1 Energy metabolism

The process of skeletal muscle contraction, involving cross bridge cycling, is maintained by immediate sources of energy or adenosine triphosphate (ATP). However, continued energy supply is necessary via metabolism of other substrates because the supply of ATP is very small. Thus ATP resynthesis occurs from other sources such as degradation of creatine phosphate (CP) and muscle glycogen breakdown during glycolysis. The oxidation of carbohydrates (CHO) and lipids (fat) also represent the major contribution to continued resynthesis of ATP during prolonged work of varied exercise intensity. Although oxidation of amino acids derived from protein sources is a possible energy source, it has been reported this substrate contributes minimally during exercise if other substrates are freely available (Wagenmakers, 1998).

The contribution of high energy phosphates, CHO and fat for energy replenishment can be influenced by the 'aerobic' or 'anaerobic' nature of the task. The existing supply of ATP and CP together with muscle glycogen represent the dominant energy yielding sources during 'high intensity', short duration activity considered to be anaerobic in nature (Withers et al., 1991). However, during prolonged 'submaximal' endurance exercise a substantial amount of ATP resynthesis occurs via oxidation of CHO and fat. Energy is supplied by utilisation of both intramuscular glycogen or through plasma glucose. The lipid source consists of plasma fatty acids or those originating from

intramuscular triglyceride reserves and those liberated from adipose tissue during lipolysis. The preferential use of fat or CHO can be influenced by such factors as diet modification (high fat or CHO) and gender (Helge, 2000; Roepstorff et al., 2001). Also, endurance trained muscle has the capacity for more efficient utilisation of lipids for energy (Holloszy and Coyle, 1984). However, the most significant influence on substrate metabolism is the interaction of the intensity and duration of exercise. Therefore, endurance events of differing duration and intensity may significantly affect the relative contribution of CHO and fat for energy metabolism.

2.4.2 Quantification of substrate metabolism during exercise

During physical activity skeletal muscle requires energy metabolism to occur via contributions from CHO but also fat related substrates. Substrate utilisation can be quantified using both indirect and direct physiological techniques (van Hall et al., 1999). The whole body oxidation of CHO or fat is typically reflected by the RER calculated from calorimetry techniques. An RER value of 0.8 represents a strong reliance on lipids, whereas a dependence on CHO would result in an RER value of > 1.0. Indeed, many research groups have demonstrating a reduced RER value during prolonged exercise at the same absolute work rate after training, have concluded that there is a greater reliance on lipids for energy in this situation (Henriksson, 1977; Keins et al., 1993). The RER in combination with $\dot{V}O_2$ and $\dot{V}CO_2$ may also be used to calculate whole body rates ($g \cdot min^{-1}$) of CHO or fat oxidation (Frayne, 1983; Peronnet and Massicotte, 1991). The oxidation rate of CHO and fat can be used as a useful measurement in terms of substrate utilisation during prolonged exercise (van Hall et al., 1999).

The plasma concentration of different metabolites is also useful in examining substrate metabolism during endurance exercise. Whilst FFA, glycerol and glucose can be quantified in the blood by standard biochemical assays, they have the disadvantage of being the end result of either appearance or disappearance in the plasma. Therefore, it is difficult to establish whether the net level of substrate in the blood is due to liberation or uptake by muscle, liver or adipose tissue in the case of FFA. Direct assessment of substrate utilisation during exercise can be measured by percutaneous needle biopsy technique or by using stable isotope methodology assessing glucose and FFA utilisation. Needle biopsies enable quantification of muscle glycogen stores before and after a bout of exercise. At the same time muscle triglyceride content can also be established. Stable isotope studies enable quantification of the appearance and disappearance of glucose and FFA. In this way, the net utilisation of these substrates during exercise can be established. The difference in the rate of appearance and disappearance of glucose has been shown to be related to CHO oxidation during exercise (Romijn et al., 1992). Thus, measuring CHO oxidation during exercise is a valid method for examining the type and quantity of substrate used during exercise (vam Hall et al., 1999).

2.4.3 Effect of exercise intensity and duration on fat and carbohydrate metabolism

Blood glucose and muscle glycogen represent the two predominant glycolytic substrates necessary for repetitive muscle contraction during exercise. The intensity of exercise can be expressed in absolute terms of relative (%) to $\dot{V}O_2max$. The absolute work rate reflects the total energy requirement or expenditure during exercise. Trained subjects

typically exercise at a high absolute work rate compared with lesser trained subjects during prolonged exercise. Therefore, the trained subject may exercise at a higher absolute work rate requiring a higher energy expenditure but elicit similar metabolic responses in terms of the contribution of fat and CHO during exercise.

An endurance task can vary in duration and intensity resulting in contrasting metabolic responses (Hargreaves, 2000). A variety of studies concerning CHO and fat utilisation during exercise have manipulated either the intensity of exercise or have introduced different length exercise trials and examined the metabolic response during these trials (Coyle et al., 1986; Romijn et al., 1993). The training status of the subject group may also influence the metabolic responses to endurance exercise partly due to adaptations in skeletal muscle affecting the choice of substrate used for energy metabolism (Holloszy and Coyle, 1984; Jansson and Kaijser, 1987). However, they may also exhibit different metabolic responses to the untrained person at similar relative exercise intensities. Furthermore, the choice of diet prior to the exercise trial in combination with the type of supplement consumed during the trial can also influence the metabolic responses during endurance exercise (Coyle et al., 1986; Hawley and Hopkins, 1995; Helge, 2000). Therefore, comparison of the metabolic responses during exercise in both sedentary and athletic populations appears in the literature. (Klein et al., 1994; Coggan et al., 2000).

Whilst the training status of subjects and diet play a major role in the preferential use of CHO or fat during endurance exercise, of greater significance is the interaction of differing duration and intensity during exercise and these affects on substrate utilisation.

During endurance competition, the intensity of exercise may be influenced by the length of the event that is completed (Padilla et al., 2000). This in turn may influence the metabolic response to that endurance task because the duration of exercise influences the exercise intensity and therefore the possible contribution of CHO or fat for energy metabolism (Hawley and Hopkins, 1995). Romijn et al. (1993) examined the effect of exercise intensity on substrate utilisation. These researchers used stable isotopic tracing to quantify of CHO and fat metabolism. These authors compared three exercise intensities (25, 65 and 85% of $\dot{V}O_2max$) in five well-trained endurance cyclists. During lower intensity exercise (~ 25-30% $\dot{V}O_2max$) more than 70% of the energy requirement is satisfied by oxidation of fat. At an exercise intensity of 40-85% of $\dot{V}O_2max$ there was a decrease in fat oxidation rate with a similar increase in CHO oxidation. Other research groups have also shown that during moderate intensity exercise the contribution of fat for energy metabolism is also lowered with a greater oxidation of CHO (Sidossis et al., 1997).

One possible limitation of these studies is that the exercise protocol was < 30 min duration. Trained athletes are known to exercise at higher exercise intensities for longer than 30 min, under these circumstances there will be substantial reduction in muscle glycogen stores. Glycogen depletion is known to result in an increase in fat utilisation for energy (Hargreaves et al., 1995; Costill et al., 1971). Therefore, it is possible that increasing the length of an exercise trial may result in a preferential use of fat related substrates. Thus, if the duration of exercise were to be increased at 85% of $\dot{V}O_2max$

(which is typical of endurance competition) it is possible that a greater contribution from fat related sources may be evident.

During exercise considered to be 'strenuous' (~80% $\dot{V}O_2max$) there is an increase in the oxidation of plasma glucose and muscle glycogen so that these substrates represent 15% and 60% of the total energy requirement respectively (Romijn et al., 1993; Roberts et al., 1998). In stark contrast, at lower exercise intensities (20-30% $\dot{V}O_2max$) the contribution of plasma fatty acids to energy metabolism is great (Romijn et al., 1993). At moderate exercise intensities (50-80% $\dot{V}O_2max$) the oxidation of plasma fatty acids and intramuscular triglycerides provides energy in similar quantity (Martin et al., 1993; Webber et al., 1993). Despite this findings, other researchers have shown that in well trained cyclists completing high intensity endurance tasks (~85% $\dot{V}O_2max$) there is a progressive shift towards higher fat oxidation rates indicating a significant contribution of these substrates (Stepto et al., 2000; Coggan et al., 2000). At the same time, there is also a greater utilisation of fat during similar high intensity exercise following a short term high fat diet (Stepto et al., 2002). Therefore, under some circumstances the contribution of fat for energy metabolism is significant during exercise higher intensity exercise. This in part may be related to the capacity of skeletal muscle for transport and subsequent oxidation of fat during exercise considered to be of high intensity (Kiens, 1997). In contrast to this data other studies demonstrate that during prolonged exercise, simulating endurance competition, better performing subjects actually demonstrate higher CHO oxidation rates during exercise > 60 min duration (O'Brien et al., 1993). These findings aside, as the

exercise intensity increases, endurance trained subjects are able to oxidise more fat (via intramuscular triglyceride stores) and less CHO during exercise (Coggan et al., 2000). Thus, despite an increase in CHO oxidation with progressively increasing exercise intensity, when compared to untrained persons, endurance trained subjects demonstrate a rightward shift in the exercise intensity (% $\dot{V}O_2$max) to fat/CHO oxidation curve (Holloszy et al., 1998; van Loon et al., 1999; Coggan et al., 2000). At the same time, as the exercise duration is prolonged the contribution of intra and extramuscular fat substrates to energy metabolism increases (Hawley and Hopkins, 1995; Rauch et al., 1998)

During exercise that can be maintained for 60 to 90 min duration there is a progressive decline in the proportion of energy derived from muscle glycogen and muscle triglycerides. At the same time, there is an increase in plasma fatty acid oxidation (Romijn et al., 1993). When the exercise duration increases above 30 min the oxidation of plasma fatty acid provides progressively more of the total energy requirements, thus compensating for the reduction in muscle glycogen and triglyceride utilisation. Typically, an increase in plasma fatty acids occurs during prolonged exercise (Kiens et al., 1993). Therefore, the increase in plasma fatty acid oxidation maybe associated with a greater 'pool' of fatty acids therefore resulting in a high oxidation rate of these substrates. However, most researches have examined the contribution of fat and CHO during prolonged exercise in untrained subjects. For example, Phillips et al. (1996) examined exercise metabolism during 90 min of cycle exercise at 60% of $\dot{V}O_2$peak. This was done before and after 5 as well as 31 days of endurance training. They found a decrease in

whole body CHO oxidation and an increase in fat oxidation. However, they observed a greater contribution from intramuscular triglycerdides for energy provision during exercise. This finding coupled with a decreased rate of appearance and disappearance of plasma fatty acids indicates that the change in fat oxidation was likely to be due to an elevated intramuscular triglycerdide utilisation. The decrease in circulating epinephrine (adrenaline) and norepinephrine (noradrenaline) (stimulators of lipolysis) also supports the finding of reduced peripheral lipolysis and plasma fatty acid utilisation. However, plasma fatty acid availability was not limited, indicating that other factors associated with cellular transport and oxidation of fatty acids may be associated with these findings (Kiens, 1997).

2.4.4 The metabolic significance of the lactate threshold

It has been suggested that the work rate at the LT is a function of both the $\dot{V}O_2$ at the LT, and submaximal economy (Hagberg and Coyle, 1983; Coyle et al., 1995). There are a variety of studies that attempt to correlate the work rate and $\dot{V}O_2$ determined at the LT with endurance performance (Farrell et al., 1979; Hagberg and Coyle, 1983; Bishop et al., 1998b). Indeed, these studies indicate that an elevated power output or velocity together with a high $\dot{V}O_2$ (% $\dot{V}O_2$max) at the LT is a prerequisite for successful endurance performance. It is widely known that an elevated $\dot{V}O_2$max is also observed in very successful endurance athletes (Lucia et al., 1998; Padilla and Mijuka, 2001). However, there is little information comparing the metabolic responses of endurance athletes with an elevated $\dot{V}O_2$max but with different LT (Coyle et al., 1988; Coyle et al., 1991).

It is widely agreed that endurance training results in a greater mitochondrial and aerobic enzyme capacity (Holloszy and Coyle, 1984). This is significant in terms of acute adaptation to incremental exercise as when the exercise intensity is raised the demand for mitochondrial respiration increases to match the supply of ATP via oxidative phosphorylation. Therefore, the oxidative capacity of skeletal muscle will effect the metabolic demand imposed on the individual muscle mitochondria with increasing exercise intensity. This in turn will influence energy metabolism, in particular glycogenolysis, lactate production and eventual fatigue manifestation. Ivy et al. (1980) have found that the $\dot{V}O_2$ at the LT expressed in absolute terms and relative to $\dot{V}O_2max$ was highly related to muscle oxidative capacity (r=0.83-0.94). Thus, this study indicates that an increase in LT maybe a reflection of an increased muscle respiratory capacity. In another study, 14 male cyclists each with a $\dot{V}O_2max$ of ~ 4.8 L·min where studied during a fatigue test comprising a single ride to exhaustion at 88% of $\dot{V}O_2max$. The LT expressed as a % of $\dot{V}O_2max$ varied between 61 and 86% for each cyclist. It was shown that those subjects possessing a high LT exercised the longest time before fatigue. In addition, muscle glycogen utilisation was lowest in subjects with a higher LT when they exercised at 79% of $\dot{V}O_2max$. Indeed, the LT was highly related (r=0.90) to muscle glycogen utilisation in this task. Therefore, this data provides evidence that energy expenditure is higher in subjects with a lower LT at the same exercise intensity when compared with subjects with a higher LT. This has implications for endurance performance as muscle glycogen depletion has traditionally been associated with fatigue

(Coyle et al., 1986). Unfortunately the relationship between the LT and muscle respiratory capacity in these trained subjects was not reported. At the same time, whilst a significant correlation has been observed between the LT and muscle respiratory capacity in untrained subjects (Ivy et al., 1980), other studies show no significant elevation in skeletal oxidative capacity has been observed following 4 weeks of high intensity endurance training despite an increase in 40-km time trial performance (Weston et al., 1997). Therefore, it is not known what influence muscle oxidative capacity has on the LT or indeed the interaction between the LT, oxidative capacity and endurance performance in response to high intensity training interventions in already trained endurance athletes.

In another study using untrained subjects, it was shown that plasma glucose disappearance rates during 30 min of exercise at 60% of $\dot{V}O_2$max were lower in subjects with a higher LT, when compared to subjects with similar $\dot{V}O_2$max but lower LT (Coggan et al., 1992). Whilst, muscle glycogen utilisation was not measured, it seems likely that the greater demand for blood glucose in the subjects with a lower LT is a reflection of the different metabolic demand experienced by these subjects during exercise of the same relative intensity. The rate of glucose disappearance has been shown to be lower in trained subjects during prolonged exercise as compared with untrained subjects with lower $\dot{V}O_2$max (Coggan et al., 1995). However the effect of an elevated LT on glucose kinetics during prolonged endurance exercise has not been investigated in trained endurance athletes.

Typically the intensity of exercise decreases with increased competition duration (Mujika and Padilla, 2001). During prolonged endurance exercise of moderate to high intensity there is a greater reliance on blood glucose and intramuscular glycogen stores (Romijn et al., 1993). However, other studies in trained and untrained subjects indicate that utilisation of fatty acids increases during prolonged exercise > 60 min (Kiens et al., 1993; Coggan et al., 2000). Other researchers present data showing fat oxidation increases as the duration of training is prolonged during high intensity training at 80% $\dot{V}O_2$max (Stepto et al., 2001). Therefore, during prolonged exercise (>60 min) at high work rates there is the possibility that fatty acid utilisation maybe greater especially in subjects with a high LT. The contribution of these substrates to total energy production under these circumstances has not been fully examined. In addition, fatty acid utilisation may be influenced by a number of skeletal muscle factors associated with cellular uptake, transport and eventual oxidation (Kiens, 1997). Therefore, a shift in metabolism towards fatty acid utilisation during prolonged exercise in subjects with an elevated LT may also be a reflection of a developed capacity to utilisation fat substrates. Many cycling time trial and triathlon races are conducted over long (>60 min) or shorter (<30 min) distances. Whilst these events may differ in terms of there physiological and metabolic demands, no studies have examined the metabolic responses during shorter or longer endurance events in subjects with similarly elevated $\dot{V}O_2$max but either a high or low LT.

2.5 Summary

The lactate threshold (LT) and onset of blood lactate accumulation (OBLA) are two physiological variables quantified by exercise physiologists during an incremental

exercise test to exhaustion. Broadly speaking, both represent the work intensity above which successive work increments results in increased muscle glycolysis, lactate accumulation and eventual fatigue (Davis, 1985; Myers and Ashley, 1997). The LT and OBLA have been shown to correlate with endurance running and cycling performance (Farrell et al., 1979; Bishop et al., 1998b). Also, these variables have been used to prescribe exercise training loads and monitor adaptation to endurance training (Padilla et al., 2000; Pyne et al., 2001). However, it is common for the LT and OBLA to be measured during incremental exercise tests where the stage duration of each work increment is markedly different, ranging between 3 min and 8 min (Coyle et al., 1983; Bishop et al., 1998a). Prolonging the stage duration during an incremental exercise test may have the effect of heightening lactate dissipation to the blood especially at high work rates (McRae et al., 1992; Smith et al., 1998). This effect may have influenced the work intensity measured at the LT and OBLA. However, the differences in work rate corresponding to the LT and OBLA measured from incremental cycle tests comprising stage durations of 3 or 8 min has not been compared especially in well trained and more recreational subjects who may differ in lactate production and clearance characteristics (Stallknecht et al., 1998). The peak power output (PPO) is another physiological variable obtained from an incremental (cycle) exercise test that has been shown to correlate with cycle time trial performance (Hawley and Noakes, 1992; Bentley et al., 1998). The PPO has been defined as the highest completed workload during an incremental exercise test comprising stages of 60 s to 5 min (Lucia et al., 1998; Padilla et al., 2000). Despite the contrast in the definitions for PPO, no study has examined the difference in this variable when obtained from incremental exercise tests comprising stages of 60 s, 3 or 5 min.

Endurance time trials in cycling and triathlon differ markedly in the duration and metabolic demand (Hausswirth et al., 1999; Padilla et al., 2000). The different metabolic demands during cycling time trials of different duration may impact on the relationship between performance in these tasks as well as PPO, the LT and OBLA. However, there are no studies that have examined the relationship between PPO, the LT and OBLA as well as cycle time trial performance of long (> 60 min) or short (<30 min) duration. Some research groups have shown that trained subjects with equal VO_2max but a 'high' LT demonstrate different metabolic responses to subjects with a low LT during short duration (30 min) high intensity activity (Coyle et al., 1988). However, there is no data examining the metabolic responses of trained cyclists with high or low LT during long (proximal to the LT) or short duration (well above the LT) endurance exercise.

CHAPTER THREE

GENERAL MATERIALS AND METHODS

CHAPTER THREE- GENERAL MATERIALS AND METHODS

3.1 Introduction

In the following four chapters outlining each study that was conducted, the specific procedures that were followed are described in the methods section. This chapter describes the experimental methodology generally used in the four studies that were conducted. The specific rationale and design of the experiments will be introduced in each of the four specific studies (Chapters four to seven).

Experiment One was conducted to compare the LT and OBLA obtained from two different incremental exercise protocols that are commonly used by exercise physiologists. Experiment two was designed to compare the LT, OBLA and peak power output (PPO) obtained from an additional two incremental exercise protocols that are commonly used to determine PPO. In experiment three the relationship between the LT and 'short' as well as 'long' cycling endurance performance was investigated. The fourth and final investigation was carried out to determine whether a trained endurance athlete (with $\dot{V}O_2max$ > 60 $ml \cdot kg^{-1} \cdot min^{-1}$) with either a high or low LT (% $\dot{V}O_2max$) would display different metabolic responses during a 'short' or 'long' set workload exercise trial specifically modelled from experiment three.

The emphasis of the first two studies concerned the methodology used for determining the LT and peak power output. The last two studies concerned the performance and

metabolic significance of the LT in endurance exercise. Therefore, in this chapter the methodology for the exercise testing (incremental exercise tests, time trial and set workload trials), collection and analysis of blood samples as well as the gas analysis data will be described.

3.2 Subjects

A total of 46 Cyclists, triathletes or mountain cyclists volunteered to participate in the research. All subjects had been involved in endurance cycle training for a minimum of twelve months prior to each study, and were cycling ~ 200 km·wk of cycling each week as part of their training. In general, each subject had been competing in triathlon or cycle racing for a period of ~ 3 yrs depending upon their training status. The subjects were recruited and subsequently used in the experiments if they were not elite and if they possessed a $\dot{V}O_2max$ > 60 ml·kg^{-1}·min^{-1} and 50 ml·kg^{-1}·min^{-1}. A $\dot{V}O_2max$ of this level is considered to be comparable to well trained but not elite cyclists (Martin et al., 2001; Mujika and Padilla, 2001). The subjects were considered to be well-trained and homogeneous in terms of $\dot{V}O_2max$.

The local research ethics committee, Bath and Avon approved the experimental protocols and procedures for each of the four studies. All the subjects who wished to participate in the experiments were informed of the aims and demands of each experiment together with any possible risks or discomforts. The research studies were explained to each subject verbally and in an information sheet (an example of the information sheet is

shown in Appendix One) prior to the subject commencing. Each subject was also screened for health status and risk factors using a pre-activity questionnaire (Appendix Two) prior to the commencement of each experiment to ensure no contraindications to the experimental protocol. The subjects also gave their written informed consent (an example of the informed consent document is shown in Appendix Three) to participate and were always free to withdraw from the experiment at any stage.

3.3 Cycle Ergometer

The cycle exercise was always performed on a stationary cycle ergometer (Schroberer Rad MeBtechnik (SRM), Weldorf, Germany). This ergometer has been specifically designed for the purpose of assessing athletes involved in cycle related activity (i.e. track or road competitions, mountain cycling or triathlon). The cycle ergometer comprises a set of cranks containing strain gauges that allow measurement of force application to the crank system. In combination with pedalling frequency, the crank system enables quantification of instantaneous power output measurements either attached to the ergometer in a laboratory or in the field with the cranks fitted to a standard bicycle (Balmer et al., 2000b; Reiser et al., 2000; Smith et al., 2001). The SRM crank system has also been confirmed as a reliable device for determining power output during submaximal exercise or calculating the maximal power output during incremental exercise testing (Balmer et al., 2000b). The power output measured by the SRM crank system has also been shown to compare favourably with other ergometers such as the Monark or Kingcycle (Balmer et al., 2000b; Reiser et al., 2000).

The design specifications of the cranks and ergometer have been previously reported (Jones and Passfield, 1998). The SRM ergometer comprises the crank system which is attached to a mounting frame and gearing system. The cranks are integrated to a 'power control unit'. The SRM cycle ergometer is designed so that the power output is calculated by the average torque (measured by force transducers housed within the crank) of one crank revolution multiplied by the angular velocity of one crank revolution via the powercontrol unit. The power output, together with heart rate (HR) and pedalling frequency data is stored for each test conducted within the power control unit and can be later downloaded to SRM software. Once downloaded to the software, the exercise session can be analysed for average or instantaneous values for power output, pedalling frequency and HR.

During exercise trials within the laboratory, power output, pedalling frequency and HR can also be observed via 'online' software downloaded to a computer. In addition, the online software can be programmed so that set workload or cadence work bouts can be executed. In this situation, the software is programmed for a set workload and regardless of the pedalling frequency (and hence angular velocity) selected by the exercising subject the power output remains at the required level via an electric field administered to the fly wheel of the ergometer.

The cycle ergometer is calibrated using the manufacturer's recommendations prior to each test. The calibration procedure requires the subject to be in a seated position and perform two backward revolutions of the cranks. Upon completion of the revolutions the

power control unit frequency setting is modified for zero power output corrected for the subjects body mass.

The SRM cycle ergometer allows ergometrical adjustments to be made so that the dimensions of the cyclists own bicycle set up are obtained. This includes seat height and length relative to the position of the cranks. The height of the drop bars together with their length relative to subjects seated position is also adjusted. Clipless pedals can also be attached to the cranks so that the cyclist may wear their own cycling shoes. Wherever possible, the ergometer was fitted to the requirements of each individual subject and recorded for repeat testing. Specific information in the SRM ergometer and crank system can be obtained from the world wide web (www. srm.de).

3.4 Exercise Testing

3.4.1 General outline

In the four studies that were completed, incremental testing (EXT) was performed in cycle exercise only. The nature of the research involved comparison of incremental exercise testing procedures for determination of the LT, OBLA and PPO. Therefore, in studies one and two, four different exercise test protocols were used. Two of these protocols were used in studies three and four after validation in the first two studies. The EXT used in experiment one involved a standard ramp test ($EXT_{60\text{-}s}$) and two lactate tests ($EXT_{3\ min}$ and $EXT_{8\ min}$). In experiment two, $EXT_{8\ min}$ was not used but replaced with another incremental exercise protocol ($EXT_{5\ min}$). In studies three and four, $EXT_{60\text{-}s}$ and

$EXT_{3\ min}$ were again used. In the second and third studies, cycling time trials were completed. In experiment four set workload exercise trials were completed. This section of the general materials and methods outlines the procedures for exercise testing that was carried out in the research.

3.4.2 Ramp Test ($EXT_{60\text{-}s}$)

The ramp test ($EXT_{60\text{-}s}$) was conducted to determine the $\dot{V}O_2$max, maximum HR (HR_{max}) and the peak power output ($PPO_{60\text{-}s}$) (Balmer et al., 2000b). The ramp test was also used to establish workloads for the remaining incremental lactate tests ($EXT_{3\ min}$, $EXT_{5\ min}$ or $EXT_{8\ min}$). This is a common method when assessing endurance trained or recreational subjects (Coyle, 1995).

The ramp test was preceded by a ten min warm up that was performed at a <150 W. The initial test workload was set at 150 W for 60 s after which power output was increased by 30 $W \cdot min^{-1}$ until exhaustion, which always occurred within 12 min. A protocol similar to this type has been shown to elicit the highest $\dot{V}O_2$ value relative to other incremental type tests (Buchfuhrer et al, 1983). A ramp style test similar to this protocol has been previously used to assess cyclists (Balmer et al., 2000b; Smith et al., 2001).

3.4.3 Lactate (step) tests

The lactate testing involved three different incremental protocols differing by stage duration (min). In experiment one, the LT and OBLA were obtained from two different tests were compared. The tests comprised either 8-9 x 3 min stages ($EXT_{3\ min}$) or 6 x 8

min stages ($EXT_{8\ min}$) both of increasing power output (W). In both these tests, the first workload represented 45% of PPO obtained from the ramp test. At the completion of the first workload each subject was required to maintain the power output that was programmed into the SRM software every three or eight min depending on the test completed. Having the test commence at a set percentage of the PPO obtained in $EXT_{60\text{-}s}$ controlled the magnitude of the workload increment. After completion of the first stage, the workload was increased by 5%. In this way, the change in the workload increment was the same for each subject (relative to a maximum level). In turn, the total duration of the test was controlled because most subjects fatigued within the same time frame. The workload increments were also determined so that an increase in $\dot{V}O_2$ of between five and eight percent would occur with each subsequent stage (Coyle, 1995; Pierce et al., 1999). The increments were also structured so that three stages would be completed below the LT, one stage would be completed at the LT and the remaining stages completed above the LT (Coyle, 1995). The subject continued the test until the six workloads were completed ($EXT_{8\ min}$) or until the required workload could not be maintained ($EXT_{3\ min}$). During experiment two, the subjects completed an additional incremental exercise protocol ($EXT_{5\ min}$) that was similar to $EXT_{3\ min}$. This involved 6-8 x 5 min stages until exhaustion.

3.4.4 Determination of peak power output (PPO).

The peak power output (PPO) during incremental exercise is obtained from an incremental exercise test to exhaustion. Both PPO or the maximum running velocity

(V_{max}) have been shown to be highly correlated with endurance cycling and running respectively (Noakes et al., 1990; Hawley and Noakes, 1992; Bentley et al., 1998).

During the each EXT the power output (W) was sampled continuously throughout the test then averaged using the SRM software. In the $EXT_{60\text{-}s}$, the average of the final min was deemed to be $PPO_{1\ min}$ (Balmer et al., 2000b). In the $EXT_{3\ min}$ and $EXT_{5\ min}$ the power output was averaged in the final 3 min or 5 min for determination of a 'sustained' PPO ($PPO_{3\ min}$ and $PPO_{5\ min}$).

3.4.5 Time trials.

In experiment three, two cycling time trials were performed, both of different duration (20 min and 90 min). Each test was performed on the SRM cycle ergometer at a freely selected pedalling cadence. The TT performed in experiment three were of duration 20 min ('short') and 90 min ('long'). The length of these trials is also common in triathlon and time trial cycling competitions. Other studies have demonstrated high reproducibility of cycle TT of short and long duration (Hickey et al., 1992; Smith et al., 2001).

Before each cycle TT, 15 min of warm up was allowed at a self-selected intensity not exceeding 45% of the $PPO_{3\ min}$ obtained during the ramp test that was always completed before the TT. At the completion of the warm up, a 60-s period was allowed where the subject was instructed to increase the power output to approximately 70 % of $PPO_{3\ min}$ the trial then commenced and the subject was free to vary the power output and pedalling frequency at their own discretion.

During the TT, electrical fans were positioned around the cyclist to allow circulation of air and heat dissipation. The two time trials were performed at the same time of day to control for any diurnal variation in performance and supervised by the same researcher.

3.4.6 Prolonged cycle exercise trials

The cycle exercise completed in experiment four involved both incremental exercise testing ($EXT_{60\text{-}s}$ and $EXT_{3\ min}$) as well as two set workload exercise trials. The two trials comprised a 90 min bout at 80% of $PPO_{3\ min}$ and 20 min at 90% of $PPO_{3\ min}$ obtained from the $EXT_{3\ min}$. The intensity (%$PPO_{3\ min}$) of the trials was modelled on the results of experiment three. The length of the trials, as with the time trials performed in experiment three, were selected because a contrast in exercise intensity is observed in TT of different duration in the field (Padilla et al., 2000). Experiment four examined the influence of the LT under circumstances of different intensity trials as in a time trial situation. Thus, it was thought on the basis of previous work quantifying the exercise intensity in TT (Padilla et al., 2000), the trials would induce contrasting metabolic responses.

Prior to each trial a 10 min warm up was allowed at an intensity of 45% of $PPO_{3\ min}$. At the completion of the warm up and a 5 min period of stretching or inactivity the trial commenced at the desired workload after a period of 60-s where the SRM ergometer was programmed at 150 W. In this period, the subject increased the pedalling cadence to the desired level. After, the initial 60-s period the workload was administered (via the SRM

software) and the subject was required to maintain this power output at a freely selected cadence.

3.5 General preparations and carbohydrate supplementation during the time trials and set workload exercise

3.5.1 General subject preparation

Before each of the trials, the subjects refrained from any high intensity/long duration training for 48-h prior to each test. They were also instructed to consume high carbohydrate (CHO) foods and regular quantities of fluid in the 48-h prior to each trial. Written guidelines were administered to each subject on with regards to correct preperation strategies. (Appendix Four). Each subject was also asked to complete a dietary record for the 24 hr period prior (excluding the fasting period) to each test so this could be replicated in the second exercise trial. The subjects reported to the laboratory after an overnight fast and having not consumed alcohol or caffeine for a full 24 hr period.

3.5.2 Carbohydrate (CHO) supplementation

During the time trials and set workload trials in experiments three and four a carbohydrate supplement was administered to each subject (Lucozade Sport, Smith Kline Beecham, United Kingdom) containing 32 g of CHO per 500 ml. The specific time point for when the supplementation was prescribed is described in the specific methods

(chapters six and seven). In general, CHO supplementation was prescribed on the basis of recommendations made by Jeukendrup and Jentjens (2000).

3.6 Body mass and height

In all studies, body mass (kg) was determined to the nearest 0.1 kg with the subject wearing only lycra cycling shorts using a balance beam (Weylux, England). The body mass was obtained immediately prior to each EXT as well as pre and post time trials (experiments two and three) and set workload trials (experiment four).

Height was evaluated to the nearest 0.1 cm using a stadiometer (Holtain Ltd). To compensate for possible shrinkage in the intervertebral disks, gentle pressure was applied upwards to the mastoid process of the subject. It was also ensured that each subject maintained heal contact with the heel plate of the stadiometer as well as the floor.

3.7 Blood collection and analysis

3.7.1 General overview

In the four studies completed two different methods were used for the collection of blood samples. In all four studies, collection of arterio-venous blood involved an incision to the left earlobe and small capillary tube samples drawn from the incision. This first method was used primarily for the collection of whole blood during the incremental exercise procedures. A second method was used in the fourth experiment for collection of venous blood. This was done using an indwelling butterfly needle inserted into the antecubital vein of the forearm.

3.7.2 Arterio-venous capillary earlobe samples

During the EXT in each experiment, capillary earlobe blood samples were obtained from an incision made to the left earlobe. Prior to collection, the incision was made using a sterile stainless steel blood lancet (Maersk Medical Ltd, Sheffield, United Kingdom). Prior to the incision being made, the ear was cleansed with a steret pre-injection swab (Seton Healthcare Group, Oldham, UK). Upon incision, the first drop of blood was discarded using a tissue. In all cases, one initial incision was made and regular cleansing and wiping using the alcoholic swab and tissue necessitated continuous bleeding. If clotting occurred another incision was made. The blood collection was completed at different points throughout each EXT. The time point of blood collection is outlined in each of the four individual experiments (Chapters four to seven).

3.7.3 Venous blood

During each set workload trial completed in experiment four, venous blood (five ml) samples were collected via a 21 gauge butterfly needle (valu-set, Becton Dickinson, Utah, USA) inserted into the anticubital vein of the forearm. A three way stopcock (Connecta, Becton Dickinson, Utah, USA) connected with a sampling line, was attached to the needle. On each occasion during exercise and recovery, a five ml blood sample was withdrawn using a 10-ml syringe (Terumo, Leuver, Belgium). Approximately two ml of saline was then injected into the sampling line after the collection of each blood sample to reduce blood clotting. Before each sample two ml of blood was withdrawn and discarded due to dilution by the injected saline. In all cases, the blood sampling was completed with

the cyclist mounted on the SRM cycle ergometer. This was done to limit changes in plasma volume (Rowell, 1993). The blood collection points during the set workload trials is outlined in chapter seven.

3.7.4 Blood lactate analysis.

Whole blood lactate analysis was completed using two separate devices in the following manner:

In experiment one and three, five microliters (μL) blood sample was immediately collected for whole blood lactate analysis via the sampling slide of a portable lactate analyser (LT 1710 Lactate Pro, KDK Corporation, Shiga, Japan). The reliability of this device, in comparison to other laboratory based devices (including the YSI blood lactate analyser), for determination of whole blood lactate concentration has been previously reported (Pyne et al., 2000). Calibration of the analyser occurred prior to each test using the manufacturer recommendations. This involved insertion of a 'test slide' of known blood lactate concentration (2.4-2.6 mM). In the blood lactate analysis process ~ five μL is sampled via capillary action into the 'test strip' (Arkray Inc., Kyoto, Japan) which is inserted prior to blood collection into the analyser. The sample is immediately analysed for blood lactate using an enzymatic reaction.

In experiment four, capillary arterio-venous blood samples were obtained during the incremental exercise testing. In addition, venous blood samples were drawn during the set workload trials. The arterio-venous blood samples (50 μL) were collected using a

Microvette (CB300, Sarstedt, Numbrecht, Germany) and immediately analysed in duplicate using a lactate analyser (2300 STAT Plus, YSI Incorporated, Yellow Springs, USA). In contrast, during the set workload trials 2.5 ml of venous blood was injected from the syringe into a 5 ml tube (Sarstedt, Humbrecht, Germany) containing an anticoagulant (EDTA).

In both cases, whole blood lactate concentration was determined using a YSI-1500 Sport L-lactate analyser (Yellow Springs Instruments, USA) calibrated prior to each testing. A quality control solution of known concentration (15 mM) was also injected into the device prior to each test. At all sampling times, 25 μL is automatically sampled by the analyser and is subsequently analysed for whole blood lactate concentration by enzymatic reaction.

3.7.5 Analysis of pH and HCO_3

During experiment four, whole blood was analysed immediately upon collection for pH and HCO_3. This procedure involved collection of ~ 180 μL of blood from the 5 ml tube via capillary action into a pH/blood gas tube (AVL Medical Instruments, Graz, Austria). The tube was inserted into an automated blood gas system (AVL, 995, AVL Medical Instruments, Graz, Austria) where the blood was injected and analysed. The blood gas analyser was calibrated prior to each experimental session used the manufacturers guidelines.

3.8 Expired air collection and Analysis

3.8.1 Equipment

In the four studies, two systems were used to collect expired breath by breath gas concentrations and volumes. In studies one and three, a laboratory based gas analyser (EX670, Morgan Medical Ltd, United Kingdom) was used. A second gas analyser (Cosmed K4, b^2, Italy) was used in studies two and four which has been used to collect metabolic data in field settings via portable telemetry (Hausswirth et al., 1997). Expired gas samples were continuously collected breath by breath for the duration of each test then averaged over a set time period depending upon the analysis required. Information concerning the time points for averaging is outlined in the specific methods of each experiment.

3.8.2 Calibration

The turbine component of each system was calibrated with known volumes (3L Hans Rudolph Syringe, Hans Rudolph, Kansas City, USA). The gas analyser of each system was also calibrated with known concentrations of gas prior (O_2, CO_2, N_2, Ar) to each test.

3.8.3 Methodological considerations for determination of maximal oxygen uptake ($\dot{V}O_2max$).

During each of the four experiments, and especially in experiments one and two, $\dot{V}O_2$max was measured as the highest 60-s average $\dot{V}O_2$ value in the test. This is in affect a '$\dot{V}O_2$peak'. Typically, the criteria for $\dot{V}O_2$max being attained is if $\dot{V}O_2$ failed to

rise (<200 ml) with a subsequent increase in workload, an RER > 1.2 and max HR within 5 b·min^{-1} of age predicted HR (220-age) (Taylor et al., 1955). However, one of main hypothesis of the research was that an increase in stage length (and in turn test duration) would result in a lower $\dot{V}O_2$peak as compared to a typical 'ramp' test. Therefore, the traditional criteria for $\dot{V}O_2$max were excluded. Hence, $\dot{V}O_2$max was determined as the highest 60-s averaged $\dot{V}O_2$ point obtained during any period of the tests performed.

3.8.4 Determination of carbohydrate and fat oxidation

During the 90 min set workload trial energy expenditure was estimated by indirect calorimetry using open circuit spirometry. The expired gases were analysed for oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) The respiratory exchange ratio (RER) was calculated automatically using the software of the gas analysis system. Whole body rates of carbohydrate (CHO) and fat oxidation (g·min^{-1}) where calculated from RER. The calculations where made from $\dot{V}O_2$ and $\dot{V}CO_2$ measurements assuming a non-protein respiratory exchange ratio using standard equations (Peronnet and Massicote, 1991).

3.9 Heart rate monitoring

Heart rate (HR) was monitored continuously throughout the incremental exercise testing, time trial and set workload exercise trials using a portable telemetrical monitor integrated to the software of the SRM ergometer.

3.10 Determination of the LT and OBLA

Lactate concentration (mM) for each individual subject were plotted against the corresponding workloads (W) completed during the EXT. Blood lactate concentration was also plotted against $\dot{V}O_2$ and HR values during each stage of the each EXT. A third order polynomial curve was then constructed from the data point. The workload at the LT was calculated using the procedures of Beaver et al., (1985). This involved determining the workload (W) at which lactate increases exponentially when the log ([La^-]) is plotted against the log. This method is thought to accurately detect the LT as opposed to visual inspection (Beaver et al., 1985). The LT were calculated by interpolation using a custom written workbook (Microsoft Excel for Windows 7.0). The HR and $\dot{V}O_2$ at the LT were interpolated from the linear line at the workload corresponding to the LT. An example of the excel worksheet used to calculate the physiological parameters is shown in Appendix Five.

3.11 Laboratory and environmental conditions

The exercise testing were conducted in the Applied Physiology Laboratory at the Department of Sport and Exercise Science, Bath University. All the exercise testing was completed under standard environmental conditions (Humidity < 50%; Temperature 18-21°C. Prior to each test, temperature and humidity were measured using an electronic thermometer (Testo, 625, Germany). Barometric pressure was also measured using a wall-mounted barometer (Griffin and George Ltd.).

3.12 Statistical analysis

The statistical analysis used is described in each individual chapter

CHAPTER FOUR

EXPERIMENT ONE

Prolonged stage duration during incremental exercise: effects on the lactate threshold and onset of blood lactate accumulation

Part of this data appears following this chapter

'Bentley, D.J., McNaughton, L.R. and Batterham, A.M. (2001). Prolonged stage duration during incremental cycle exercise: effects on the lactate threshold and onset of blood lactate accumulation. *European Journal of Applied Physiology* 85 (3-4):351-357'.

CHAPTER FOUR – EXPERIMENT ONE

4.1 Introduction

The physiological response to incremental exercise is often conducted by measuring plasma or whole blood lactate concentration (mM) coupled to oxygen consumption ($\dot{V}O_2$) and work rate (Coyle, 1995; Farrell et al., 1979; Weltman et al., 1990). The $\dot{V}O_2$ at a blood lactate concentration of 4 mM (OBLA) or the lactate threshold (LT) have been used to predict endurance performance or distinguish between well trained and elite trained time trial cyclists with similar $\dot{V}O_2$max (Coyle et al., 1991; Tanaka and Matsuura, 1984).

Incremental exercise tests to determine the LT and OBLA, may be conducted immediately proceeding or on a different day to an incremental ramp test involving short (<60-s) stage duration to determine $\dot{V}O_2$max. The second incremental test may involve multiple (continuous or discontinuous) work stages of 8 to 10 min duration to determine the LT and OBLA (Coyle et al., 1991; Coyle et al., 1983). It is also popular to use a single incremental exercise test of stages 3 to 5 min duration to determine a 'sustained' PPO and $\dot{V}O_2$max together with the LT and OBLA (Bentley et al., 1998; Bishop et al., 1998b). Other scientists suggest workloads of duration 3-6 min is not valid for establishing the blood lactate response to incremental exercise (Thoden, 1991; Foxdal et al., 1996).

The use of different exercise testing procedures for determining maximal and submaximal physiological variables has a number of important consequences. Firstly, two individual tests performed on different days may be considered time consuming for athletic populations. However, a single test of stage duration 3 to 5 min may result in a lower $\dot{V}O_2$ value at maximal exertion than that obtained in a shorter 'ramp' test (Froelicher et al., 1974; Buchfunrer et al., 1983). At the same time, the peak power output (PPO), measured as the highest sustained power output during incremental exercise of stages 3-5 min duration, will also be lower than that compared with a test of stages 60-s duration. If the LT and OBLA are being expressed relative to a maximal level, lower maximal values may inflate the submaximal threshold values expressed as a % of a maximum value. Another potentially influential factor, is the length of stages used during the submaximal stage of the incremental test. By increasing the length of stages the appearance of lactate in the blood may change regardless of any work rate increment (Smith et al., 1998). $\dot{V}O_2$ kinetics may also be different in tests with longer workload duration especially above the LT (Jones et al., 1999). Both of these factors may affect subsequent physiological threshold values expressed in absolute terms or relative (%) to $\dot{V}O_2$max.

Different research groups have compared lactate and ventilation responses to different incremental exercise tests with stage durations less than 5 min (Coen et. 2000; Prioux et al., 1997). There is little data examining stages > 5 min when changes in both $\dot{V}O_2$

kinetics and blood lactate concentration may markedly differ to that of a test with stages < 3 min. At the same time, there are no studies comparing a 'well trained' and more recreational group of subjects, who may exhibit different physiological responses to submaximal exercise at the same relative exercise intensity (Marcinik et al., 1991).

Aims:

(1) To establish whether there is a significant difference in the workload (W), HR ($b \cdot min^{-1}$) and $\dot{V}O_2$ ($L \cdot min^{-1}$) at the LT and OBLA using either a 3 min or 8 min incremental exercise test protocol.

(2) To establish whether there is a significant difference in the $\dot{V}O_2max$ and HR_{max} reached during an incremental exercise test to exhaustion involving either 60-s or 3 min work increments.

(3) To establish whether the LT and OBLA differs when expressed as a % of PPO, $\dot{V}O_2max$ and HR_{max} obtained from a 3 min stage test or from a 8 min stage incremental test coupled with a ramp test comprising stages of 60-s duration.

(4) To establish whether two populations of cyclists differing in $\dot{V}O_2max$ (and therefore training status) exhibit significantly different metabolic responses and in turn different LT and OBLA values during a 3 min stage test or from a 8 min stage incremental test.

4.2 Methods

4.2.1 Subjects

Twelve male subjects with mean ± standard deviation (SD) age 31.2 ± 4.9 yrs, body mass 76.7 ± 6.3 kg and $\dot{V}O_2$max 60.1 ± 7.5 ml·kg^{-1}·min^{-1} participated in the study. Six subjects were assigned to a recreational (REC) group and six to a well-trained group (WT) group on the basis of performance in the incremental ramp test (PPO and $\dot{V}O_2$max in WT subjects ~400 W and ~65 ml·kg^{-1}·min^{-1} respectively) (Jeukendrup et al., 2000). The WT group consisted of triathletes (n=3) who had recently competed internationally in age group multisport events, elite mountain cyclists (n=2) and a British Cycling Federation (BCF) category two cyclist. The REC were active in triathlon or road cycling at club level, but had not competed at an international level.

4.2.2 Experimental Design

Each subject performed three incremental exercise tests over a two-week period on an SRM electrically braked cycle ergometer system (SRM, Schroberer Rad MeBtechnik, Weldorf, Germany). The first test was a 'ramp' test ($EXT_{60\text{-}s}$) to exhaustion for determination of maximum 'minute' workload (W) ($PPO_{60\text{-}s}$), $\dot{V}O_2$max (L·min^{-1}) and HR_{max} (b·min^{-1}) (Balmer et al., 2000b). It was hypothesised that this test would elicit the highest $\dot{V}O_2$ and HR value (Buchfuhrer et al., 1983). At the same time, conducting this test prior to a submaximal exercise test is a standard procedure when determining the LT (Coyle, 1995). The second and third tests were two separate continuous incremental lactate tests (EXT) involving work stages of either 3 min ($EXT_{3\ min}$) or 8 min ($EXT_{8\ min}$)

duration. The $EXT_{3\ min}$ involved ~8 stages until exhaustion (Bentley et al., 1998; Bishop et al., 1998a). Like the $EXT_{60\text{-}s}$, the maximum 'sustained workload' ($PPO_{3\ min}$) together with HR_{peak} and $\dot{V}O_2max$ were obtained from this test. In contrast, the $EXT_{8\ min}$ involved six stages only with PPO, $\dot{V}O_2max$ and HR_{max} values not obtained. The $EXT_{60\text{-}s}$ was always completed first whilst the $EXT_{3\ min}$ and $EXT_{8\ min}$ were performed in a randomised order. Each test was separated by at least 48-h.

Capillary blood samples were obtained via a small incision made to the left earlobe in the final 30-s of each workload during both the EXT. The blood sample was immediately analysed for blood lactate concentration (mM) using a portable lactate analyser (LT 1710 Lactate Pro, KDK Corporation, Shiga, Japan) (Pyne et al., 2000) (Refer to General Materials and Methods). Expired gases were also continuously collected breath by breath using a mass spectrometer (EX670, Morgan Medical Ltd, United Kingdom) during each EXT for determination of $\dot{V}O_2$ ($L \cdot min^{-1}$). The $\dot{V}O_2max$ was calculated as the highest 60-s average in any stage of the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$. Power output (W) and HR ($b \cdot min^{-1}$) were sampled every 1-s during each test using the powercontrol unit integrated to the SRM system. The power output and HR, together with $\dot{V}O_2$ were averaged in the final 60-s of each workload of each test. Also, these variables were averaged in the 3rd minute of each stage of the $EXT_{8\ min}$. These measurements were used to calculate the power output (W), $\dot{V}O_2$ and HR corresponding to the LT and OBLA (See 'General Materials and Methods'). These physiological variables were expressed in absolute values and expressed relative (%) to $PPO_{60\text{-}s}$, HR_{max} and $\dot{V}O_2max$ obtained from the $EXT_{60\text{-}s}$. The

LT and OBLA determined from the $EXT_{3\ min}$ were expressed relative to maximal levels obtained during the $EXT_{3\ min}$.

4.2.3 Statistical Analysis.

The physical characteristics of the two groups (age, height and body mass) as well as $\dot{V}O_2max$ ($L \cdot min^{-1}$ and $ml \cdot kg^{-1} \cdot min^{-1}$), $PPO_{60\text{-}s}$ (W), for the WT and REC groups obtained from the $EXT_{60\text{-}s}$, were compared using a students t-test for independent samples.

The power output ($\%PPO_{60\text{-}s}$) and $\dot{V}O_2$ ($L \cdot min^{-1}$) measured in the first six stages of the $EXT_{3\ min}$ and all stages during the $EXT_{8\ min}$ were compared using a two factor (test protocol x subject group) Analysis of Variance (ANOVA). Whole blood lactate concentration (mM) measured at the completion of each workload in the $EXT_{8\ min}$ and following completion of the first 6 workloads in $EXT_{3\ min}$, was also compared using a series of single factor ANOVA. The power output averaged in the final min of these workloads during the $EXT_{3\ min}$ and $EXT_{8\ min}$ as well as the third min of $EXT_{8\ min}$ was also compared using a series of single factor ANOVA.

The workload, $\dot{V}O_2$ and HR (measured in absolute terms and relative to the respective maximal values obtained in $EXT_{60\text{-}s}$ and $EXT_{3\ min}$) corresponding to the LT and the OBLA, for the WT and REC groups obtained from the $EXT_{3\ min}$ and $EXT_{8\ min}$ were compared using a two factor (test protocol x subject group) ANOVA. Additional two factor ANOVA were calculated to compare the PPO (W), $\dot{V}O_2max$ ($L \cdot min^{-1}$) and the

HR_{max} ($b \cdot min^{-1}$) obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$. The Levene test was used to determine homogeneity of variance. Pearson-product moment correlations were calculated to examine the relationship between $\dot{V}O_2max$ and PPO obtained from $EXT_{60\text{-}s}$ and $EXT_{3\ min}$. Significance was set at $p<0.05$ for all tests.

4.3 Results

4.3.1 Characteristics of the participating subjects

Maximal oxygen uptake ($L \cdot min^{-1}$) and $PPO_{60\text{-}s}$ (W) obtained during the $EXT_{60\text{-}s}$ were significantly ($p<0.01$) higher in the WT when compared to the REC cyclists (Table 4.3.1). There was also a significant ($p<0.05$) difference in $\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$) and height (cm) between the WT and REC subjects (Table 4.3.1). There were no significant differences in body mass (kg) or age (yrs) between the two subject groups (Table 4.3.1).

Table 4.3.1 Physical characteristics, maximal oxygen uptake ($\dot{V}O_2max$) and maximum power output (PPO) obtained in the $EXT_{60\text{-}s}$ of subjects in the recreational (REC) and well-trained (WT) cyclists.

	WT (n=6)	REC (n=6)
Age (yrs)	29.8 ± 6.1	32.5 ± 3.3
Height (cm)	185.2 ± 5.1	178.8 ± 4.9*
Body Mass (kg)	75.7 ± 6.6	77.8 ± 6.4
$\dot{V}O_2max$ ($L \cdot min^{-1}$)	4.85 ± 0.12	4.29 ± 0.28**
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	64.6 ± 6.4	55.6 ± 5.9*
$PPO_{60\text{-}s}$ (W)	422.2 ± 23.5	329.2 ± 13.7**

* Significantly different from WT ($p<0.05$)

** Significantly different from WT ($p<0.01$)

4.3.2 Maximal physiological variables in the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$

The $\dot{V}O_2max$ ($L \cdot min^{-1}$) and PPO (W) in the WT trained subjects was significantly ($p<0.01$) higher compared to the REC subjects in either the $EXT_{60\text{-}s}$ or $EXT_{3\ min}$. (Table 4.3.2). The $\dot{V}O_2max$ ($L \cdot min^{-1}$) was lower when measured from the $EXT_{3\ min}$ as compared with $EXT_{60\text{-}s}$ and this approached statistical significance ($p<0.06$) (Figure 4.3.1). The PPO obtained in the $EXT_{60\text{-}s}$ was significantly ($p<0.01$) higher than in the $EXT_{3\ min}$ (Figure 4.3.2) At the same time, there was a significant ($p<0.01$) interaction effect whereby the difference between the $PPO_{60\text{-}s}$ and $PPO_{3\ min}$ was significantly ($p<0.01$)

greater in the WT subjects (Table 4.3.2). The HR_{max} was not significantly different in the $EXT_{60\text{-}s}$ as compared with $EXT_{3\ min}$ regardless of whether the subject was WT or REC.

There was a significant correlation between $PPO_{60\text{-}s}$ and $\dot{V}O_2max$ ($L \cdot min^{-1}$) ($r=0.80$; $p<0.01$). There was also a significant correlation between $PPO_{3\ min}$ and $\dot{V}O_2max$ ($r=0.81$; $p<0.01$). The $PPO_{3\ min}$ and $PPO_{60\text{-}s}$ were also highly correlated ($r=0.94$; $p<0.01$). A significant correlation was also found between $\dot{V}O_2max$ in the $EXT_{3\ min}$ and the same variable in $EXT_{60\text{-}s}$ ($r=0.82$; $p<0.01$).

Table 4.3.2. Mean (±SD) maximal oxygen uptake ($\dot{V}O_2max$), peak power output (PPO) and maximum HR (HR_{max}) obtained in the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ of subjects in the recreational (REC) and well-trained (WT) group.

	WT		REC	
	$EXT_{60\text{-}s}$	$EXT_{3\ min}$	$EXT_{60\text{-}s}$	$EXT_{3\ min}$
$\dot{V}O_2max$ ($L \cdot min^{-1}$)	$4.85 \pm 0.12_x$	$4.75 \pm 0.26_x$	$4.29 \pm 0.28_y$	$4.07 \pm 0.30_y$
PPO (W)	$422.2 \pm 23.5_x$	$352.9 \pm 21.4_y$	$329.2 \pm 13.7_z$	$292.0 \pm 17.0_z$
HR_{max} ($b \cdot min^{-1}$)	$182.6 \pm 9.9_x$	$179.5 \pm 5.2_x$	$184.0 \pm 7.3_x$	$179.5 \pm 8.6_x$

Different subscripts^{x,y,z} indicate a significant difference in a row (e.g. $\dot{V}O_2max$ only)

Figure 4.3.1. Mean (±SD) $\dot{V}O_2max$ ($L \cdot min^{-1}$) obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ (n=12) (no significant difference).

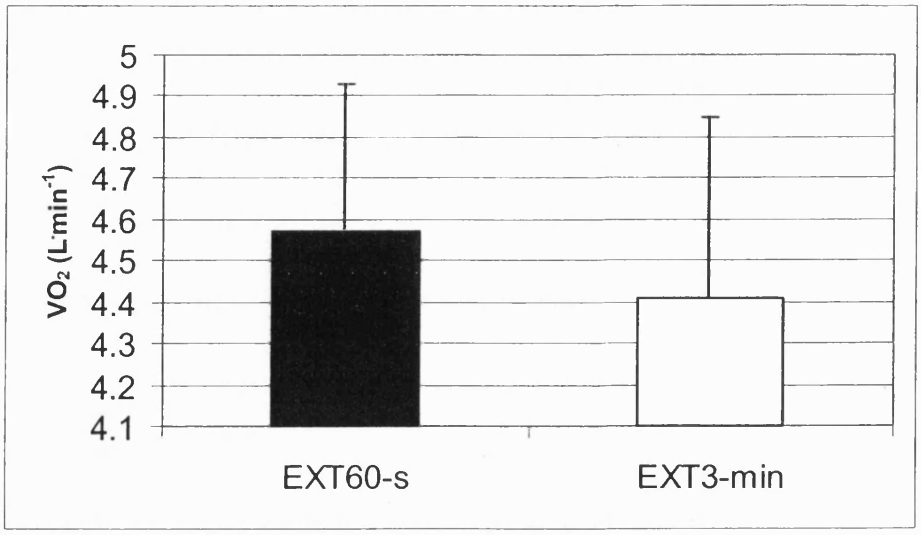


Figure 4.3.2. Mean (±SD) peak power output (PPO) (W) obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ (n=12) (**p<0.01).

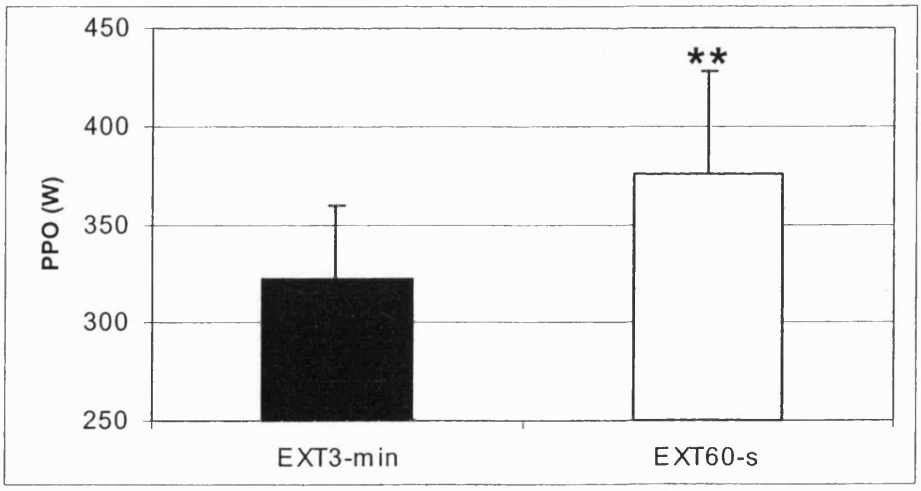
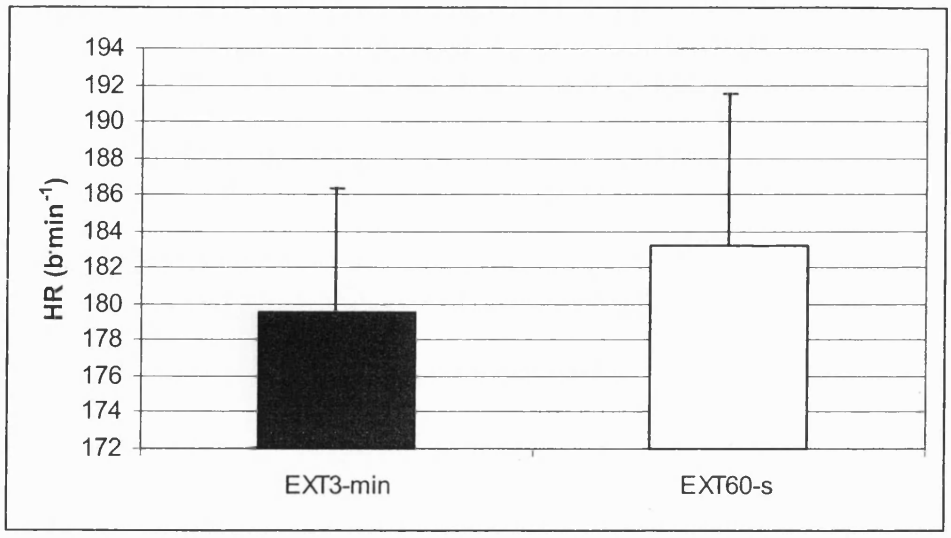


Figure 4.3.3. Mean (±SD) maximum heart rate (HR_{max}) ($b \cdot min^{-1}$) obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ (n=12) (no significant difference).



4.3.3 Physiological adaptations during the $EXT_{3\ min}$ and $EXT_{8\ min}$

The power output (% $PPO_{60\text{-}s}$) generated by each subject significantly ($p<0.01$) increased with each stage of the EXT. However, the power output (% $PPO_{60\text{-}s}$) during each stage of the $EXT_{3\ min}$ and $EXT_{8\ min}$ was statistically similar (Table 4.3.3). The WT and REC cyclists also exercised at a statistically similar power output relative to $PPO_{60\text{-}s}$ at the three time periods averaged during each stage of either the $EXT_{3\ min}$ or $EXT_{8\ min}$.

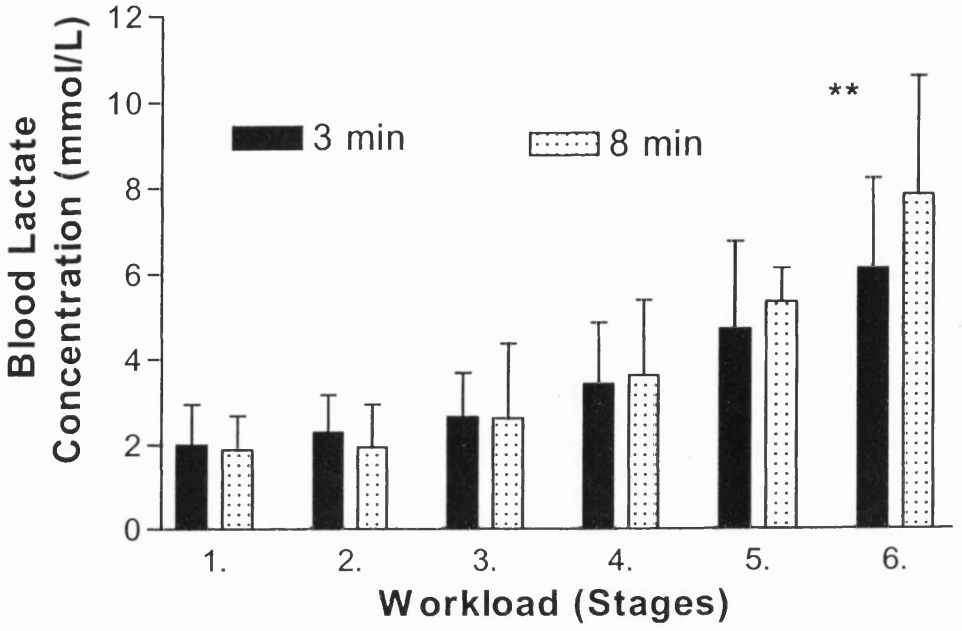
Table 4.3.3. Power output (W) as a percentage (%) of maximum workload (PPO) in the third min of the $EXT_{8\ min}$ as well as the final min of the $EXT_{3\ min}$ and $EXT_{8\ min}$ (n=12).

	Test		
	$EXT_{3\ min}$	$EXT_{8\ min}$	
Stage	3rd min	3rd min	8th min
1	44.3 ± 8.8	46.2 ± 4.2	47.4 ± 3.7
2	52.7 ± 5.0	53.1 ± 4.7	53.4 ± 4.3
3	58.2 ± 5.1	58.6 ± 4.9	58.7 ± 4.3
4	64.3 ± 5.2	63.8 ± 4.2	64.3 ± 4.5
5	70.1 ± 6.3	69.6 ± 4.8	69.5 ± 4.5
6	75.4 ± 6.1	75.5 ± 4.3	76.4 ± 4.6

No significant differences

The blood lactate concentration (mM) following the second workload of the $EXT_{8\ min}$ was significantly lower ($p<0.05$) in the WT as compared to the REC group (Table 4.3.4). When the data were pooled, there was a significant ($p<0.01$) increase in blood lactate at the completion of the 6th workload in the $EXT_{8\ min}$ as compared to the $EXT_{3\ min}$ (Table 4.3.4 and Figure 4.3.4).

Figure 4.3.4 Mean ±SD Blood lactate concentration (mmol/L) at the completion of each workload during the EXT_{3min} and EXT_{8min}.



** Significantly ($p<0.01$) different EXT_{3min}.

Table 4.3.4. Mean (±SD) blood lactate concentration (mM) at the completion of each workload during the $EXT_{3\ min}$ and $EXT_{8\ min}$ in the WT (n=6) and REC (n=6) cyclists.

Workload	$EXT_{3\ min}$		$EXT_{8\ min}$	
	WT	REC	WT	REC
1	$2.0 \pm 1.0_x$	$2.0 \pm 1.0_x$	$1.7 \pm 0.5_x$	$2.1 \pm 1.0_x$
2	$2.3 \pm 0.8_x$	$2.3 \pm 1.0_x$	$1.4 \pm 0.2_y$	$2.5 \pm 1.2_x$
3	$2.5 \pm 0.8_x$	$2.8 \pm 1.3_x$	$1.8 \pm 0.3_x$	$3.4 \pm 2.2_x$
4	$2.9 \pm 0.7_x$	$3.9 \pm 1.8_x$	$2.9 \pm 0.2_x$	$4.3 \pm 2.3)_x$
5	$3.9 \pm 0.7_x$	$5.5 \pm 2.7_x$	$4.4 \pm 0.6_x$	$6.3 \pm 3.2_x$
6	$5.3 \pm 0.8_x$	$6.9 \pm 2.8_x$	$6.7 \pm 1.3_y$	$9.0 \pm 3.4_y$

Subscripts indicate significant differences within a row

Oxygen consumption ($L \cdot min^{-1}$) at each time period in each stage was significantly higher ($p<0.01$) in the WT subjects as compared to the REC cyclists (Table 4.3.5). However, despite the elevation of $\dot{V}O_2$ in the WT subjects, there was no significant difference in the WT and REC subjects for the $\dot{V}O_2$ determined at the completion of each workload in the $EXT_{3\ min}$ or in the third as well as the final min of each individual stage of the $EXT_{8\ min}$. When the results of the WT and REC were combined $\dot{V}O_2$ was significantly ($p<0.05$) higher in the first workload in the $EXT_{8\ min}$ as compared to $EXT_{3\ min}$ or the 3rd min of $EXT_{8\ min}$. This finding aside, there was no significant differences in $\dot{V}O_2$ measured at each time period during each stage of the $EXT_{8\ min}$ or $EXT_{3\ min}$.

Table 4.3.5. Mean (±SD) oxygen consumption ($\dot{V}O_2$) ($L \cdot min^{-1}$) in the final min of each workload during the $EXT_{3\ min}$ and $EXT_{8\ min}$ as well as the third min of the $EXT_{8\ min}$ in the well trained (WT) (n=6) and recreational (REC) (n=6) cyclists.

Workload	Test					
	$EXT_{3\ min}$		$EXT_{8\ min}$			
	3^{rd} min		3^{rd} min		8^{th} min	
	WT	REC	WT	REC	WT	REC
1	$2.60\pm0.35_x$	$2.21\pm0.12_y$	$2.71\pm0.33_x$	$2.12\pm0.21_y$	$2.80\pm0.38_x$	$2.24\pm0.15_y$
2	$2.92\pm0.32_x$	$2.46\pm0.18_y$	$3.04\pm0.39_x$	$2.32\pm0.47_y$	$3.02\pm0.40_x$	$2.45\pm0.31_y$
3	$3.17\pm0.30_x$	$2.72\pm0.17_y$	$3.30\pm0.43_x$	$2.66\pm0.19_y$	$3.31\pm0.43_x$	$2.74\pm0.18_y$
4	$3.42\pm0.34_x$	$2.97\pm0.18_y$	$3.58\pm0.39_x$	$2.91\pm0.20_y$	$3.68\pm0.44_x$	$2.96\pm0.23_y$
5	$3.70\pm0.33_x$	$3.21\pm0.20_y$	$3.87\pm0.44_x$	$3.10\pm0.23_y$	$3.95\pm0.41_x$	$3.18\pm0.18_y$
6	$3.97\pm0.29_x$	$3.43\pm0.26_y$	$4.19\pm0.49_x$	$3.40\pm0.15_y$	$4.28\pm0.42_x$	$3.50\pm0.17_y$

$Subscripts_{x,y}$ indicate significant ($p<0.01$) differences in a row (e.g. workload no. 1)

4.3.4 The LT and OBLA calculated from the $EXT_{3\ min}$ and $EXT_{8\ min}$

Regardless of whether data from $EXT_{3\ min}$ or $EXT_{8\ min}$ (in combination with $EXT_{60\text{-}s}$) was used, the power output (W) and $\dot{V}O_2$ ($L \cdot min^{-1}$) corresponding to both the LT and OBLA were significantly ($p<0.01$) higher in the WT than the REC cyclists (Table 4.3.6). However, the HR ($b \cdot min^{-1}$) corresponding to the LT and OBLA did not significantly differ between WT and REC (Table 4.3.6). The power output (W) at the LT was significantly ($p<0.05$) higher in the $EXT_{3\ min}$ as compared to the $EXT_{8\ min}$ in the WT cyclists, but not the REC subjects (Table 4.3.6). No such effect was found for the power

output (W) corresponding to OBLA. There was also no significant effect of the exercise protocol on the HR ($b \cdot min^{-1}$) or $\dot{V}O_2$ ($L \cdot min^{-1}$) corresponding to the LT or the $\dot{V}O_2$ or HR corresponding to the OBLA in the WT or REC subjects (Table 4.3.6). This result was also the same when the results in the WT an REC subjects were combined. (Figure 4.3.5 and 4.3.7). In addition, there was no significant difference in the power output corresponding to the LT and OBLA obtained from the $EXT_{3\ min}$ and $EXT_{8\ min}$ (Figure 4.3.6)

Table 4.3.6. Mean (±SD) oxygen consumption ($\dot{V}O_2$) ($L \cdot min^{-1}$), heart rate (HR) ($b \cdot min^{-1}$) and workload (W) at the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) obtained during $EXT_{3\ min}$ and $EXT_{8\ min}$ for the well trained (WT) (n=6) and recreational (REC) cyclists (n=6).

Variable		$EXT_{3\ min}$		$EXT_{8\ min}$	
		WT	REC	WT	REC
LT	$\dot{V}O_2$	$3.50 \pm 0.53_x$	$2.60 \pm 0.14_y$	$3.14 \pm 0.42_x$	$2.72 \pm 0.15_y$
	HR	$152.6 \pm 12.1_x$	$143.8 \pm 7.3_x$	$138.4 \pm 18.2_x$	$154.8 \pm 18.5_x$
	W	$264.0 \pm 42.2_x$	$193.2 \pm 15.0_y$	$225.2 \pm 26.6_z$	$201.8 \pm 18.4_y$
OBLA	$\dot{V}O_2$	$3.62 \pm 0.41_x$	$2.88 \pm 0.29_y$	$3.94 \pm 0.43_x$	$2.80 \pm 0.52_y$
	HR	$156.2 \pm 12.1_x$	$154.8 \pm 9.7_x$	$159.2 \pm 12.7_x$	$152.4 \pm 10.8_x$
	W	$275.4 \pm 38.6_x$	$219.4 \pm 21.0_y$	$280.6 \pm 21.0_x$	$209.0 \pm 32.0_y$

Subscripts indicate significant differences within a row

Figure 4.3.5. The mean (±SD) $\dot{V}O_2$ ($L \cdot min^{-1}$) corresponding to the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) obtained from the $EXT_{3\ min}$ and $EXT_{8\ min}$. No significant ($p>0.05$) differences between the $EXT_{3\ min}$ and $EXT_{8\ min}$.

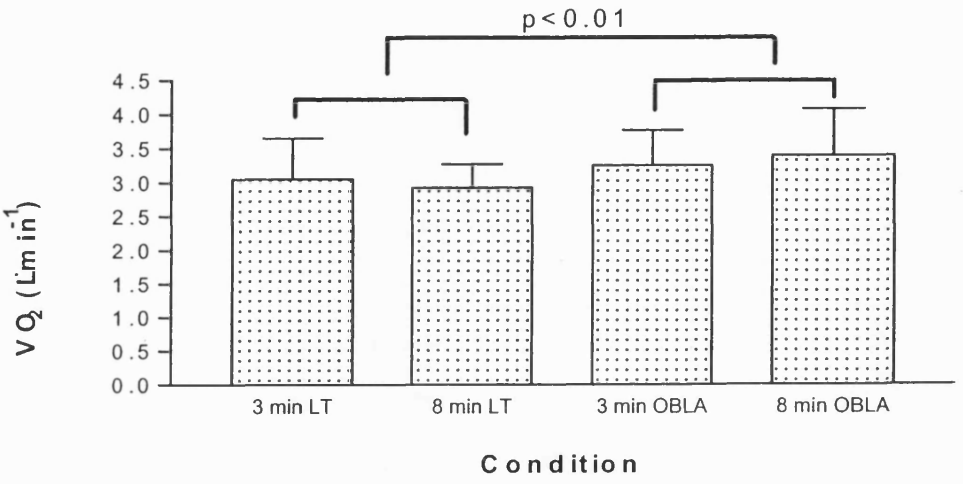


Figure 4.3.6. The mean (±SD) power output (W) corresponding to the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) obtained from the $EXT_{3\ min}$ and $EXT_{8\ min}$. No significant ($p>0.05$) differences between the $EXT_{3\ min}$ and $EXT_{8\ min}$.

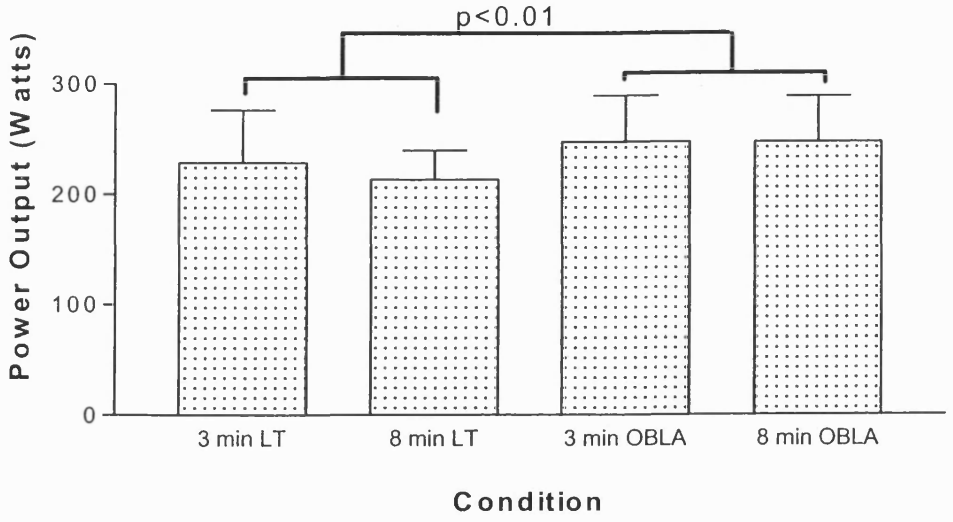


Figure 4.3.7. The mean (±SD) heart rate ($b \cdot min^{-1}$) corresponding to the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) obtained from the $EXT_{3\ min}$ and $EXT_{8\ min}$

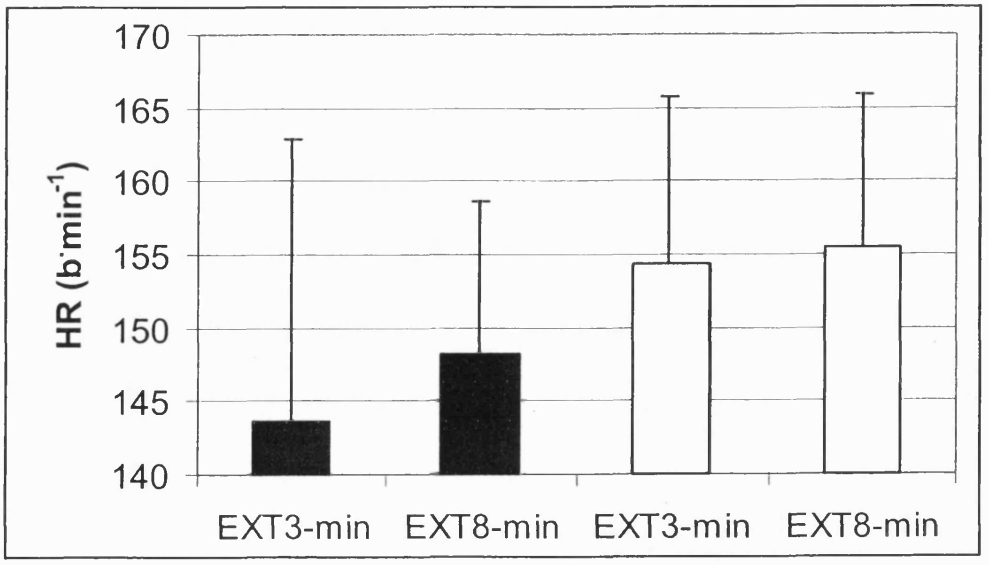


Table 4.3.7. The mean (±SD) Oxygen consumption ($\dot{V}O_2$), heart rate (HR) and workload (W) at the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) expressed as a % of maximal values obtained from the $EXT_{3\ min}$ or $EXT_{8\ min}$ (coupled with $EXT_{60\text{-}s}$) for the well trained (WT) and recreational (REC) cyclists

Variable		$EXT_{3\ min}$		$EXT_{8\ min}$	
		WT	REC	WT	REC
LT	$\dot{V}O_2$	$66.4 \pm 10.4_x$	$67.0 \pm 10.3_x$	$72.8 \pm 12.0_x$	$61.5 \pm 5.4_x$
	HR	$77.1 \pm 8.0_x$	$82.8 \pm 9.3_x$	$83.7 \pm 7.3_x$	$78.8 \pm 4.2_x$
	W	$64.8 \pm 6.9_x$	$68.2 \pm 10.4_x$	$63.5 \pm 9.4_x$	$59.0 \pm 5.0_x$
OBLA	$\dot{V}O_2$	$75.3 \pm 10.0_x$	$68.1 \pm 10.0_y$	$82.3 \pm 12.3_x$	$71.4 \pm 13.1_y$
	HR	$88.2 \pm 5.5_x$	$83.8 \pm 4.6_x$	$85.6 \pm 5.6_x$	$85.1 \pm 5.3_x$
	W	$79.7 \pm 3.6_x$	$72.9 \pm 9.4_x$	$66.3 \pm 8.5_y$	$66.1 \pm 5.0_y$

Subscripts indicate significant differences within a row

The LT (% $\dot{V}O_2max$) was higher in the $EXT_{8\ min}$ (coupled with the $EXT_{60\text{-}s}$) compared to $EXT_{3\ min}$ in the WT compared to the REC. However, this affect was not significant (Table 4.3.7). There was no significant difference in the LT (%PPO) when determined from $EXT_{3\ min}$ or $EXT_{8\ min}$ in the WT or REC. The LT ($\%HR_{max}$) was higher in WT, but lower in the REC, when measured from $EXT_{8\ min}$ compared to $EXT_{3\ min}$ and this approached significance ($p<0.09$) (Table 4.3.7). There was also no significant difference in the OBLA expressed as a % of $\dot{V}O_2max$ or HR when determined from $EXT_{3\ min}$ or $EXT_{8\ min}$ in the WT or REC cyclists (Table 4.3.7). However, the OBLA (%PPO) was significantly higher

in the both WT and REC in the $EXT_{3\ min}$ compared to $EXT_{8\ min}$ (Table 4.3.7). There were no significant differences in the power output, HR or $\dot{V}O_2$ corresponding to the LT relative to maximum levels in the WT and REC. The OBLA expressed as a % of $\dot{V}O_2max$ was higher in the WT subjects compared to the REC and this approached significance ($p<0.09$). This finding aside, there was no significance differences in the power output or HR corresponding to the OBLA (expressed relative to maximum values) in REC or WT.

When the WT and REC subjects were pooled the OBLA (%PPO) was significantly ($p<0.01$) higher when measured in $EXT_{3\ min}$ as compared to $EXT_{8\ min}$ (Table 4.3.8). However, this result was not evident for the LT (expressed as a % of $\dot{V}O_2max$ or PPO) or the OBLA (expressed as % $\dot{V}O_2max$). There was no significant difference in the LT ($\%HR_{max}$) when obtained from $EXT_{8\ min}$ or $EXT_{3\ min}$ (Table 4.3.8). There was also no significant difference in the OBLA (% HR_{max}) when measured from the $EXT_{8\ min}$ and $EXT_{3\ min}$ (Table 4.3.8).

Table 4.3.8. The mean (±SD) Oxygen consumption ($\dot{V}O_2$), heart rate (HR) and workload (W) at the lactate threshold (LT) and Onset of Blood Lactate Accumulation (OBLA) expressed as a % of maximal values obtained from the $EXT_{3\ min}$ or $EXT_{8\ min}$

Variable		$EXT_{3\ min}$	$EXT_{8\ min}$
LT	$\dot{V}O_2$	66.7 ± 8.1	66.7 ± 10.3
	HR	79.9 ± 8.8	80.6 ± 6.6
	W	66.5 ± 8.6	61.1 ± 7.3
OBLA	$\dot{V}O_2$	76.8 ± 13.4	71.7 ± 10.2
	HR	86.0 ± 5.4	85.4 ± 5.1
	W	76.4 ± 7.7	60.2 ± 6.6**

** Significantly ($p<0.01$) different from $EXT_{3\ min}$

4.4 Discussion

A number of different incremental exercise protocols have been designed to determine coupled workrate, $\dot{V}O_2$ and blood lactate measurements in trained athletes (Farrell et al., 1979; Horowitz et al., 1994). This experiment was conducted to determine whether the LT or OBLA differed when measured from two separate incremental exercise tests with step increments of either three min ($EXT_{3\ min}$) or eight min ($EXT_{8\ min}$) duration. Furthermore, the results of each test were compared in a group of well trained as opposed to a recreational group of cyclists. The main findings of experiment one including

combined group and incremental exercise protocol affects on the LT and OBLA are summarised in Table 4.4.1.

Table 4.1.1 A summary of the main affects of group and incremental exercise protocol on the LT and OBLA found in experiment one.

Variable	Affect		
	Group	Protocol	Group x Protocol
LT (W)	**Yes**	No	**Yes**
LT ($l \cdot min^{-1}$)	**Yes**	No	No
LT ($b \cdot min^{-1}$)	No	No	No
OBLA (W)	**Yes**	No	No
OBLA ($l \cdot min^{-1}$)	**Yes**	No	No
OBLA ($b \cdot min^{-1}$)	No	No	No
LT (%PPO)	No	No	No
LT (% $\dot{V}O_2max$)	No	No	No
LT (%HR_{max})	No	No	No
OBLA (%PPO)	No	**Yes**	No
OBLA (% $\dot{V}O_2max$)	**Yes**	No	No
OBLA (%HR_{max})	No	No	No

In this experiment it was hypothesised that the prolonged duration of each workload during the $EXT_{8\ min}$ combined with the different ability levels of the two groups of cyclists, would result in contrasting blood lactate and $\dot{V}O_2$ measurements at the end of each workload. This in turn would affect the coupled $\dot{V}O_2$ and blood lactate values at the LT and the OBLA. The results demonstrate that the absolute workload (W) corresponding to the LT of the WT subjects (but not the REC) was significantly higher

when calculated from the results of the $EXT_{3\ min}$ as compared with the $EXT_{8\ min}$. The OBLA (%PPO) was also significantly higher in the $EXT_{3\ min}$ as compared with $EXT_{8\ min}$. These findings aside, there were no significant effects of training status (WT or REC) or exercise protocol on the $\dot{V}O_2$ or HR corresponding to the LT or OBLA obtained from either the $EXT_{3\ min}$ or $EXT_{8\ min}$.

The appearance of blood lactate is a combination of both production and elimination (MacRae et al., 1992). During low intensity exercise lactate is shuttled from the muscle cell and may be eliminated by less metabolically active tissues (Brooks, 2000). At the same time oxidative metabolism is preferential at lower work rates, which will result in less production and possible appearance of blood lactate (Jeukendrup et al., 1999). However, during higher intensity exercise greater than the so called LT point, blood lactate accumulation is more pronounced and continues to rise with prolonged exercise despite constant work rate (Smith et al., 1998). The ability to reduce muscle lactate production and increase elimination will dictate the appearance of this metabolite in the blood (Brooks, 2000). The implication of this is that well trained subjects may exhibit different lactate accumulation responses during prolonged exercise than untrained subjects at the same relative work rate. At the same time, prolonging the stage duration may heighten either lactate production or elimination thereby influencing eventual accumulation of this metabolite.

The WT group of cyclists recruited for this experiment were superior to the REC group in terms of PPO and $\dot{V}O_2max$. Thus, it is likely that the WT subjects may have had a greater

metabolic capacity to reduce blood lactate accumulation at each relative work rate compared to the REC subjects (Pilegaard et al., 1994). Regardless of training status, during sustained exercise of greater than 3 min duration, blood lactate accumulation will be more pronounced especially at work rates above the LT (Jones et al., 1999). At the same time, it has also been recently shown that training status effects the metabolic response during prolonged exercise above the LT (Baldwin et al., 2000). The results of this study demonstrate that during the $EXT_{8\ min}$, when compared to the REC group, the WT subjects had a significantly lower blood lactate concentration at low work rates. At higher work rates, there was a trend for blood lactate concentration to be greater in the REC cyclists, especially in the $EXT_{8\ min}$. However, the blood lactate concentration remained statistically similar in the REC when compared to the WT subjects. Thus, it is likely that the similar blood lactate response at higher work rates in the $EXT_{8\ min}$ and $EXT_{3\ min}$ in both groups may explain why the power output corresponding to the OBLA was statistically similar when calculated from the results of either EXT. It has been suggested that prolonging the stage duration during incremental exercise may promote greater lactate dissipation (Smith et al., 1997). Therefore, this is one reason (in combination with different lactate diffusion capacity) why the LT may have been higher in the $EXT_{3\ min}$ than the $EXT_{8\ min}$ in the WT subjects.

Whilst other reports have detailed changes in ventilation and blood lactate parameters with different exercise protocols using stages of duration < five min (Bishop et al., 1998a; Coen et al., 2000; McLellan 1985; Prioux et al. 1997) only one previous study has directly investigated the effects on LT and fixed blood lactate measurements of different

exercise protocols using stage durations of < three min and > five min (Weltman et al., 1990). These authors compared the $\dot{V}O_2$, running velocity ($m \cdot min^{-1}$) and HR values corresponding to the LT and 4.0 mM (OBLA) points during incremental treadmill exercise involving either continuous three min or discontinuous ten min workloads. The results showed the different testing protocols did not result in any significant effects on the coupled $\dot{V}O_2$ and velocity measurements at the LT or 4 mM blood lactate point, which was comparable to the present study in terms of the power output and $\dot{V}O_2$ at the OBLA but not the power output at the LT. However, the discontinuous (ten min stage) tests used by Weltman et al., (1990) were conducted over three separate days. This in turn may have reduced the residual effects of the previously completed workloads that may have been influential in the present experiment. Furthermore, Weltman et al. (1990) used running exercise. This may elicit differential metabolic responses to cycling exercise at the same relative exercise intensity (Jones and McConnell, 1999). Furthermore, the results presented by Weltman et al. (1990) were not compared relative to a maximal workload or to $\dot{V}O_2$max. The results of this experiment demonstrate that whilst there was a significant increase in PPO in the $EXT_{60\text{-}s}$ as compared to $EXT_{3\ min}$, there was no significant difference in the $\dot{V}O_2$max measured from these two EXT. Also, the OBLA (%PPO) was significantly higher in $EXT_{3\ min}$ compared with $EXT_{8\ min}$. The latter result may in part be due to the higher PPO obtained from the $EXT_{60\text{-}s}$ which was used in combination with the $EXT_{8\ min}$. It may also be due to differences in lactate kinetics with the different protocols. Regardless of the mechanisms, the OBLA obtained from a protocol comprising 8 min stage duration expressed as a % of PPO measured in an

incremental ramp test may be lower compared with an incremental test comprising 3 min stages.

It is interesting that there was only a weak correlation between PPO and $\dot{V}O_2$max in the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ (r=0.80). In another study, it was shown that PPO was highly correlated (r=0.97; p<0.01) to $\dot{V}O_2$max in a group of 100 cyclists (Hawley and Noakes, 1992). It is possible that the lower correlation co-efficient found in this experiment was due to lower subject numbers. However, because the subjects in this study were not all well trained (i.e. the REC group), it was expected that the two variables would be highly correlated. However, that was not the case with only ~ 60% of the variation in $\dot{V}O_2$max being explained by the PPO in both instances. Therefore, it is possible that the relationship between PPO and $\dot{V}O_2$max is uncoupled during incremental exercise in subjects of different training status, the mechanism for which is yet to be established. This aside, it is suggested that PPO is not sufficient to be used as an indirect measure of $\dot{V}O_2$max. Therefore, the PPO should not be used as a predictor of $\dot{V}O_2$max.

The present experiment was also able to compare a WT and REC group of athletes during cycle exercise that was controlled in terms of the relative exercise intensity completed during each workload in each test. With this in mind, the results of this experiment indicate that training status has a limited physiological effect on the OBLA results obtained from a 3 min or 8 min stage incremental exercise test. However, it is possible that the workload at the LT may be influenced by the protocol used to determine this

variable in more highly trained subjects. This is especially true as there were no significant effects of the EXT protocol on the power output corresponding to the LT when data from the WT and REC groups were combined.

Another interesting but secondary finding of this study was $\dot{V}O_2$ was similar in the final min of both the $EXT_{3\ min}$ and $EXT_{8\ min}$ as well as in the third min of $EXT_{8\ min}$. It has been suggested that the $\dot{V}O_2$ slow component or a delayed rise in $\dot{V}O_2$ occurs as a result of metabolic acidosis during prolonged exercise (Carter et al., 2000). Indeed, it has been shown that the change in $\dot{V}O_2$ from the third to the seventh min during six successive incremental work rates is associated with the increase in blood lactate above the LT (Jones et al., 1999). The results of the present experiment indicate that the delayed increase in $\dot{V}O_2$ during sustained exercise above the LT did not occur in either of the WT or REC cyclists that participated in this experiment. However, further studies are required to examine the effects of the magnitude of work rate increment during different exercise modes on the $\dot{V}O_2$ slow component during incremental exercise.

In summary the results of this study show that in well trained cyclists the power output corresponding to the LT is lower when obtained from an incremental exercise test comprising stages of 8 min duration than from a test comprising 3 min stages. Furthermore, the OBLA (%PPO) is lower in an incremental test comprising 8 min stages coupled with a ramp test of 60-s stages. Aside from these findings an incremental exercise test comprising stages of 3 min duration is sufficient to quantify the LT and

OBLA expressed in absolute terms or relative to PPO or $\dot{V}O_2max$. However, the PPO can only be measured from incremental exercise tests comprising stages of 60-s to 5 min duration (Paton and Hopkins, 2001). Therefore, the PPO can not be obtained from a test comprising 8 min stages. Another experiment is required to investigate the validity of PPO (and the LT or OBLA) obtained from an incremental test of stages ranging between 60-s and 5 min duration.

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ORIGINAL ARTICLE

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Prolonged stage duration during incremental cycle exercise: effects on the lactate threshold and onset of blood lactate accumulation

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Abstract The aim of this study was to investigate whether increasing the duration of workloads from 3 min to 8 min during incremental exercise would influence workload (W), oxygen consumption ($\dot{V}O_2$) and heart rate (HR) at the lactate threshold (LT) and the onset of blood lactate accumulation(OBLA). Two groups of six male cyclists were assigned to a well-trained (WT) and recreational (REC) group on the basis of their performance in a maximal incremental ramp test. Each subject then performed two incremental lactate tests (EXT) consisting of six workloads of either 3 min ($EXT_{3\text{-min}}$) or 8 min ($EXT_{8\text{-min}}$) duration. At the completion of each workload whole capillary blood samples were obtained for the determination of blood lactate (BLa) concentration (mM). Power output (Watts, W), HR and $\dot{V}O_2$ were averaged in the final minute of each workload as well as in the third minute of the $EXT_{8\text{-min}}$. The workload, HR and $\dot{V}O_2$ at the LT and OBLA were subsequently determined from the data of $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$. The results demonstrate that workload and $\dot{V}O_2$, but not HR, at the LT and OBLA were higher in the WT cyclists. At the same time, the workload at the LT obtained from the results of the $EXT_{3\text{-min}}$ was significantly ($P<0.05$) higher then the value obtained in the $EXT_{8\text{-min}}$ in the WT subjects but not the REC subjects. However, the workload, $\dot{V}O_2$ and HR at the OBLA, together with the $\dot{V}O_2$ and HR at the LT were not significantly different when calculated from data obtained from $EXT_{3\text{-min}}$ or $EXT_{8\text{-min}}$. The data obtained in this study suggest that incremental exercise protocols using workloads of duration longer than 3 min have the effect of increasing the workload at the LT in well-trained cyclists. However, the OBLA determined in exercise tests using stage increments of either 3 min or 8 min is similar in cyclists of different training status.

Keywords Adaptation · Athletes · Blood lactate · Incremental exercise · Oxygen consumption · Workload

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Introduction

The physiological response to incremental exercise is often conducted by measuring the plasma or whole blood lactate (BLa) concentration coupled with oxygen consumption ($\dot{V}O_2$) (Coyle 1995; Farrell et al. 1979; Weltman et al. 1990). The $\dot{V}O_2$ at a BLa concentration of 4 mM (OBLA) or the lactate threshold (LT), for example, have been used to predict distance running performance or distinguish between well-trained and elite-trained time-trial cyclists with similar maximal oxygen uptake ($\dot{V}O_2max$) (Coyle et al. 1991; Tanaka and Matsuura 1984). In addition, the response to endurance training has been quantified by measuring the $\dot{V}O_2$ at the LT (LT_{VO_2}) in previously sedentary subjects (Coyle et al. 1983). Another study has reported a strong relationship between skeletal muscle oxidative capacity and the LT_{VO2} (Ivy et al. 1980).

A potentially influential factor in all of these investigations is the type of incremental exercise protocol that is used to determine the workload or $\dot{V}O_2$ at the LT and OBLA (Bishop et al. 1998b; Coyle et al. 1983, 1991). Several research groups, for example, have used a series of 10-min exercise bouts on different test days in trained or sedentary subjects (Coyle et al. 1983; Farrell et al. 1979). Others (Coyle et al. 1991; Horowitz et al. 1994) have used 5-min staged protocols to determine the LT_{VO2} in well-trained cyclists. More recently 3-min and 4-min staged protocols have been used to determine the LT during cycle exercise in triathletes or female cyclists (Bishop et al. 1998b; Hoogeveen and Schep 1997).

During incremental exercise muscle and BLa accumulation may change at different rates relative to the exercise intensity being completed (Chwalbinska-

Moneta et al. 1989). At exercise intensities below the LT, and where a "steady state" is achievable, BLa accumulation remains minimal and may even decrease with increasing exercise duration. However, at work rates above the LT, BLa concentration increases with time despite no change in work rate (Smith et al. 1998). In addition to changes in BLa accumulation, $\dot{V}O_2$ may also rise until a steady state has been reached, usually after approximately 3 min (Whipp and Wasserman 1972). At work rates that evoke a marked increase in Bla, that is greater than the LT, $\dot{V}O_2$ does not reach a steady state but continues to rise (Jones et al. 1999). This delayed phase of $\dot{V}O_2$ kinetics has been termed "the $\dot{V}O_2$ slow component" (Whipp 1994). Therefore, the delayed increase in $\dot{V}O_2$ during higher intensity exercise beyond the LT, together with the change in BLa accumulation, may influence the workload and $\dot{V}O_2$ at the LT or OBLA when different incremental exercise protocols are used.

There have been a number of research groups who have compared lactate and ventilation responses to different incremental exercise tests with stage durations of less than 5 min (Coen et al. 2000; Prioux et al. 1997). There are few data examining stages of less than 5 min when changes in oxygen uptake kinetics and BLa accumulation may change markedly. In one study, Weltman et al. (1990) showed that 3-min or 10-min incremental step tests resulted in no significant difference in the workload or $\dot{V}O_2$ at the LT or OBLA. However, other researchers have shown that the physiological response to exercise may change depending upon the length of stages during incremental exercise used to determine the workload of the exercise (Foxdal et al. 1994, 1996). However, these investigations were conducted without an untrained control group, or they did not couple BLa and $\dot{V}O_2$ measurements in the analysis.

During cycle exercise it has been reported that well-trained subjects are able to exert more efficient force during the down phase of the pedalling cycle (Coyle et al. 1991). Thus, during prolonged submaximal exercise of the same relative exercise intensity, the recruitment patterns of slow and fast motor units and subsequent BLa production may differ between cyclists of varying ability level. Indeed it has been suggested that changes in motor recruitment patterns may influence changes in BLa during prolonged cycle exercise (Marcinik et al. 1991).

The existing literature therefore suggests that cycling efficiency, together with the length of the incremental exercise protocol, may influence coupled BLa and $\dot{V}O_2$ measurements. Therefore, the purpose of this investigation was to measure the workload and $\dot{V}O_2$ at the LT and OBLA using a 3-min or an 8-min incremental step test protocol. Furthermore, two populations of cyclists that differed in aerobic capacity were assessed to determine the effects of training status on the metabolic response during these incremental exercise tests.

Methods

Subjects

Twelve male subjects with the following physical characteristics [mean (SD)]: age 31.2 (4.9) years, body mass 76.7 (6.3) kg and $\dot{V}O_2$max 60.1 (7.5) ml·kg^{-1}·min^{-1} volunteered to participate in the study. Six subjects were assigned to a recreational (REC) group and six to a well-trained group (WT) group based on their performance in the ramp test (maximum workload in WT subjects ≥400 W). The WT group consisted of triathletes (n=3) who had recently competed internationally in age group multisport events, elite mountain cyclists (n=2) and a British Cycling Federation (BCF) category two cyclist. The REC were active in triathlon or road cycling at club level, but had not competed at an international level. The methods and possible risks were explained verbally and in writing to each subject and all signed informed consent. The protocol was approved by the local research ethics committee.

Experimental design

Each subject completed three exercise tests over a 2-week period performed on an SRM electrically braked cycle ergometer system (SRM, Schroberer Rad MeBtechnik, Weldorf, Germany). A previous report has demonstrated the reliability of power output during incremental exercise tests using the SRM system (Balmer et al. 2000).

The first test was an incremental ramp test to exhaustion to determine the maximum workload (W) (PPO) and $\dot{V}O_2$max (l·min^{-1}). The second and third tests included two separate continuous incremental lactate tests (EXT) involving six stages of either 3 min ($EXT_{3\text{-min}}$) or 8 min ($EXT_{8\text{-min}}$) duration. The ramp test was always completed first whilst the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ were performed in a randomized order. Each test was separated by at least 48 h and followed 24 h of inactivity or low-intensity/duration exercise.

Ramp test

The ramp test was preceded by a 10-min warm up that was performed at a self-selected intensity representing less than 50% of $\dot{V}O_2$max. The test commenced at a workload of 125 W and increased at 30-W·min^{-1} increments until volitional exhaustion or if the subject was not able to produce the desired work rate. Power output (W) was sampled continuously throughout the test then averaged in the final minute to maximum workload (PPO) (Balmer et al. 2000). Expired gases were also sampled continuously breath by breath throughout the test using an online mass spectrometer (EX670, Morgan Medical, England) and the data were averaged every 15 s. The system was calibrated with known gas concentrations and volumes prior to each test according to manufacturer's specifications. Heart rate (beats·min^{-1}) was sampled at 5-s intervals throughout the test by a HR monitor (Polar, Vantage, Finland). $\dot{V}O_2$max was deemed to have been achieved if the respiratory exchange ratio was greater than 1.2, HR was within 5 beats·min^{-1} of the age-predicted maximum and $\dot{V}O_2$ failed to increase with subsequent increments in power output. $\dot{V}O_2$max was deemed to be the highest $\dot{V}O_2$ measured during any averaged 15-s period.

Incremental lactate tests

Whole BLa and $\dot{V}O_2$ measurements were obtained during two EXT. The $EXT_{3\text{-min}}$ test involved six continuous stages each of 3 min duration while the $EXT_{8\text{-min}}$ test involved six stages of 8 min duration. In both EXT, the first workload represented 50–60% of $\dot{V}O_2$max depending upon the ability level of the cyclist. At the completion of the first workload each subject was required to increase the power output every 3 or 8 min depending on the test completed. The workload increments were determined so that an

increase in $\dot{V}O_2$ of between 5% and 8% would occur with each subsequent stage (Coyle 1995; Pierce et al. 1999). The increments were also structured so that three stages would be completed below the LT, one stage would be completed at the LT and the final two stages completed above the LT (Coyle 1995). The subject continued the test until the six workloads were completed or until the required workload could not be maintained.

During both tests the power output was collected continuously whilst HR was sampled at 5-s intervals. Power output and HR were then averaged in the last minute of each workload during the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ as well as in the third minute of $EXT_{8\text{-}min}$. Similarly, expired gases were sampled continuously breath by breath for $\dot{V}O_2$ as described previously. The average $\dot{V}O_2$ was then determined for the final minute of each workload during the $EXT_{3\text{-}min}$ and the $EXT_{8\text{-}min}$ as well as the third minute of the $EXT_{8\text{-}min}$. Power output was also averaged for the duration of each workload during both the EXT.

Capillary whole blood samples were obtained via a small incision made in the left earlobe in the final 30 s of each workload during both EXT. The blood sample was subsequently analysed for BLa (mM) using a portable lactate analyser (LT 1710 Lactate Pro, KDK, Shiga, Japan). The reliability of this device for measuring whole BLa concentration is reported elsewhere (Pyne et al. 2000). The analyser was calibrated prior to each test using the manufacturer's recommendations.

Blood lactate, $\dot{V}O_2$ and HR values were plotted against the average power output during each stage of the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ respectively. A curvilinear line of best fit was then constructed for BLa against power output and a linear line was constructed for power output and $\dot{V}O_2$, and $\dot{V}O_2$ and HR. The power output at the LT was calculated using the procedures of Beaver et al. (1985). This method is thought to accurately detect the LT as opposed to visual inspection (Beaver et al. 1985). The workload at the OBLA was also interpolatedfrom the curvilinear line and deemed to be the point eliciting a BLa concentration of 4 mM (Sjodin and Jacobs 1981). The HR and $\dot{V}O_2$ at the LT and OBLA were interpolated from the linear line at the workload corresponding to the LT and OBLA respectively.

Statistical analysis

The physical characteristics of the two groups (age, height and body mass) as well as maximal oxygen uptake ($l \cdot min^{-1}$ and $ml \cdot kg^{-1} \cdot min^{-1}$) and PPO (W) for the WT and REC groups obtained from the ramp test were compared using independent sample *t*-tests. The power output during each of the tests was expressed as a percentage of PPO. A series of single-factor (test protocol) analysis of variance (ANOVA) with repeated measures and between-subject comparisons (subject group) was used to compare the average power output during each stage of the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$. Whole BLa concentration at the completion of each workload in each EXT, together with power output and $\dot{V}O_2$ averaged in the final minute of each workload during the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ as well as the third minute of $EXT_{8\text{-}min}$ were also analysed using a series of single-factor (test protocol) ANOVA with repeated measures and between-subject comparisons (subject group). The workload, $\dot{V}O_2$ and HR at the LT and the OBLA for the WT and REC groups obtained from the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ were compared using a single-factor ANOVA with repeated measures and between-subject comparisons (subject group). Significance was set at $P < 0.05$.

Results

The differences in the physical characteristics of the two groups of subjects can be seen in Table 1. Maximal oxygen uptake and PPO obtained during the ramp test were significantly higher in the WT when compared to the REC cyclists (Table 1). Although the power output significantly ($P < 0.01$) increased during each stage of each EXT, there were no significant ($P > 0.05$) differences in the power output (relative to PPO) in the $EXT_{3\text{-}min}$ or $EXT_{8\text{-}min}$ (Table 2). Furthermore, the WT and REC cyclists exercised at a statistically similar power output relative to PPO at the three time periods during each stage of either the $EXT_{3\text{-}min}$ or $EXT_{8\text{-}min}$.

BLa concentrations were similar at the completion of each workload in each EXT in both the WT and REC subjects. However, the BLa concentration following the second workload of the $EXT_{8\text{-}min}$ was significantly lower ($P < 0.03$) in the WT as compared to the REC group (Table 3). At the same time, the BLa concentration was significantly ($P < 0.005$) elevated in both the WT and

Table 1 Physical characteristics, maximal oxygen uptake ($\dot{V}O_2max$) and maximum power output (*PPO*) obtained in the incremental ramp test of subjects in the recreational (*REC*) and well-trained (*WT*) cyclist groups

Variable	WT ($n=6$)	REC ($n=6$)
Age (years)	29.8 (6.1)	32.5 (3.3)
Height (cm)	185.2 (5.1)	178.8 (4.9)*
Body mass (kg)	75.7 (6.6)	77.8 (6.4)
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	4.85 (0.12)	4.29 (0.28)**
$\dot{V}O_2max$ ($ml \cdot kg \cdot min^{-1}$)	64.6 (6.4)	55.6 (5.9)*
PPO (W)	422.2 (23.5)	329.2 (13.7)**

*Significantly different from WT ($P < 0.05$)
**Significantly different from WT ($P < 0.01$)

Table 2 Power output (*W*) as a percentage (%) of maximum workload (*PPO*) in the third minute of the $EXT_{8\text{-}min}$ as well as the final min of the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ ($n=12$)

Stage	Test		
	$EXT_{3\text{-}min}$ 3rd min	$EXT_{8\text{-}min}$	
		3rd min	8th min
1	44.3 (8.8)	46.2 (4.2)	47.4 (3.7)
2	52.7 (5.0)	53.1 (4.7)	53.4 (4.3)
3	58.2 (5.1)	58.6 (4.9)	58.7 (4.3)
4	64.3 (5.2)	63.8 (4.2)	64.3 (4.5)
5	70.1 (6.3)	69.6 (4.8)	69.5 (4.5)
6	75.4 (6.1)	75.5 (4.3)	76.4 (4.6)

Table 3 Blood lactate concentration (*[BLa]*, mM) at the completion of each workload during the $EXT_{3\text{-}min}$ and $EXT_{8\text{-}min}$ in the WT ($n=6$) and REC ($n=6$) cyclists

Workload	$EXT_{3\text{-}min}$		$EXT_{8\text{-}min}$	
	WT	REC	WT	REC
1	$2.0\ (1.0)_x$	$2.0\ (1.0)_x$	$1.7\ (0.5)_x$	$2.1\ (1.0)_x$
2	$2.3\ (0.8)_x$	$2.3\ (1.0)_x$	$1.4\ (0.2)_y$	$2.5\ (1.2)_x$
3	$2.5\ (0.8)_x$	$2.8\ (1.3)_x$	$1.8\ (0.3)_x$	$3.4\ (2.2)_x$
4	$2.9\ (0.7)_x$	$3.9\ (1.8)_x$	$2.9\ (0.2)_x$	$4.3\ (2.3)_x$
5	$3.9\ (0.7)_x$	$5.5\ (2.7)_x$	$4.4\ (0.6)_x$	$6.3\ (3.2)_x$
6	$5.3\ (0.8)_x$	$6.9\ (2.8)_x$	$6.7\ (1.3)_y$	$9.0\ (3.4)_y$

Subscripts indicate significant ($P < 0.03$) differences within a *row*

REC cyclists following completion of the final workload in the $EXT_{8\text{-min}}$ as compared to the $EXT_{3\text{-min}}$ (Table 3; Fig. 1).

Oxygen consumption was significantly higher ($P < 0.01$) higher in the WT subjects at each time period in each stage as compared to the REC cyclists (Table 4). However, despite the elevation of $\dot{V}O_2$ in the WT subjects, there was no significant effect of training status on the change in $\dot{V}O_2$ determined at the completion of each workload in the $EXT_{3\text{-min}}$ or in the third as well as the final minute of each individual stage of the $EXT_{8\text{-min}}$. When the results of the WT and REC were combined, $\dot{V}O_2$ was significantly ($P = 0.05$) higher in the final minute of the first workload in the $EXT_{8\text{-min}}$ as compared to the final minute of $EXT_{3\text{-min}}$ or the third minute of $EXT_{8\text{-min}}$. This finding aside, there were no significant differences in $\dot{V}O_2$ measured at each time period during each stage of the $EXT_{8\text{-min}}$ or $EXT_{3\text{-min}}$.

Whichever EXT was used for analysis, the workload corresponding to the LT (LT_W) and at OBLA ($OBLA_W$), as well as $\dot{V}O_2$ at the LT (LT_{VO2}) and at OBLA ($OBLA_{VO2}$) were all significantly higher in the WT group of cyclists (Table 5). However, the HR at the LT (LT_{HR}) and at OBLA ($OBLA_{HR}$) did not significantly differ between the WT and REC cyclists. The LT_W was significantly ($P < 0.05$) higher in the $EXT_{3\text{-min}}$ as compared to the $EXT_{8\text{-min}}$ in the WT cyclists. With the exception of the LT_W the different exercise protocols had no effect on each of these variables regardless of the cyclists' training status (Table 5, Figs. 2, 3).

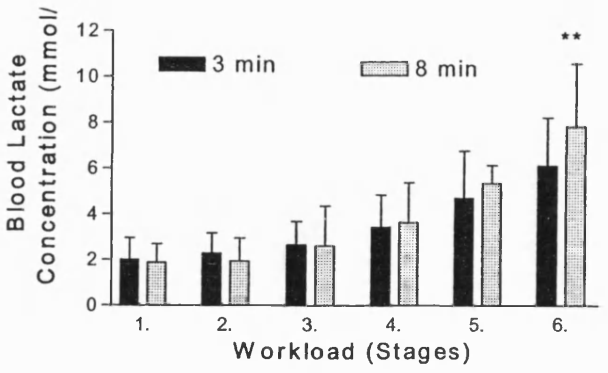

Fig. 1 Blood lactate concentration (*[BLa]*) [mean (SD)] at the completion of each workload during the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$. ($EXT_{3\text{-min}}$ An incremental lactate test consisting of six workloads of 3 min duration, $EXT_{8\text{-min}}$ as before but 8 min duration.) **Significantly ($P < 0.01$) different than $EXT_{3\text{-min}}$ data

Discussion

A number of different incremental exercise protocols have been designed to determine coupled workload, $\dot{V}O_2$ and BLa measurements in trained athletes (Farrell et al. 1979; Horowitz et al. 1994). The purpose of this investigation was to compare coupled whole BLa and $\dot{V}O_2$ as well as power output and BLa measurements obtained

Table 4 Oxygen consumption ($\dot{V}O_2$) ($l \cdot min^{-1}$) in the final minute of each workload during the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ as well as the third minute of the $EXT_{8\text{-min}}$ in the well trained (*WT*) ($n = 6$) and recreational (*REC*) ($n = 6$) cyclists

Workload	Test					
	$EXT_{3\text{-min}}$		$EXT_{8\text{-min}}$			
	3rd min		3rd min		8th min	
	WT	REC	WT	REC	WT	REC
1	$2.60\ (0.35)_x$	$2.21\ (0.12)_y$	$2.71\ (0.33)_x$	$2.12\ (0.21)_y$	$2.80\ (0.38)_x$	$2.24\ (0.15)_y$
2	$2.92\ (0.32)_x$	$2.46\ (0.18)_y$	$3.04\ (0.39)_x$	$2.32\ (0.47)_y$	$3.02\ (0.40)_x$	$2.45\ (0.31)_y$
3	$3.17\ (0.30)_x$	$2.72\ (0.17)_y$	$3.30\ (0.43)_x$	$2.66\ (0.19)_y$	$3.31\ (0.43)_x$	$2.74\ (0.18)_y$
4	$3.42\ (0.34)_x$	$2.97\ (0.18)_y$	$3.58\ (0.39)_x$	$2.91\ (0.20)_y$	$3.68\ (0.44)_x$	$2.96\ (0.23)_y$
5	$3.70\ (0.33)_x$	$3.21\ (0.20)_y$	$3.87\ (0.44)_x$	$3.10\ (0.23)_y$	$3.95\ (0.41)_x$	$3.18\ (0.18)_y$
6	$3.97\ (0.29)_x$	$3.43\ (0.26)_y$	$4.19\ (0.49)_x$	$3.40\ (0.15)_y$	$4.28\ (0.42)_x$	$3.50\ (0.17)_y$

Subscript indicate significant ($P < 0.01$) differences within a *row*

Table 5 Oxygen consumption ($\dot{V}O_2$) ($l \cdot min^{-1}$), heart rate (*HR*) ($beats \cdot min^{-1}$) and workload (*W*) at the lactate threshold (*LT*) and onset of blood lactate accumulation (*OBLA*) obtained during $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ for the well-trained (*WT*) ($n = 6$) and recreational (*REC*) cyclists ($n = 6$)

Variable	$EXT_{3\text{-min}}$		$EXT_{8\text{-min}}$	
	WT	REC	WT	REC
LT_{VO2}	$3.50\ (0.53)_x$	$2.60\ (0.14)_y$	$3.14\ (0.42)_x$	$2.72\ (0.15)_y$
LT_{HR}	$152.6\ (12.1)_x$	$143.8\ (7.3)_x$	$138.4\ (18.2)_x$	$154.8\ (18.5)_x$
LT_W	$264.0\ (42.2)_x$	$193.2\ (15.0)_y$	$225.2\ (26.6)_z$	$201.8.8\ (18.4)_y$
$OBLA_{VO2}$	$3.62\ (0.41)_x$	$2.88\ (0.29)_y$	$3.94\ (0.43)_x$	$2.80\ (0.52)_y$
$OBLA_{HR}$	$156.2\ (12.1)_x$	$154.8\ (9.7)_x$	$159.2\ (12.7)_x$	$152.4\ \pm(10.8)_x$
$OBLA_W$	$275.4\ (38.6)_x$	$219.4\ (21.0)_y$	$280.6\ (21.0)_x$	$209.0\ (32.0)_y$

Subscripts indicate significant ($P < 0.05$) differences within a *row*

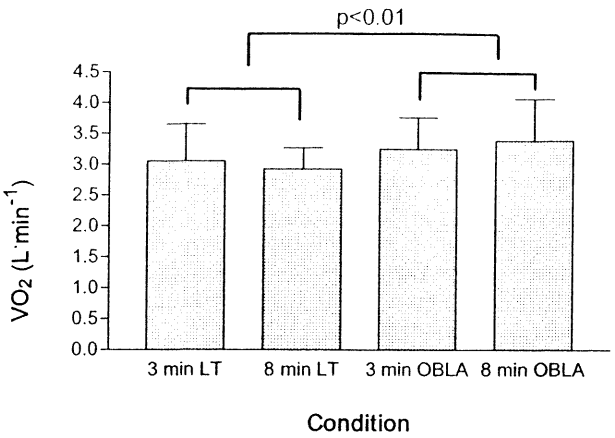

Fig. 2 Oxygen consumption at the lactate threshold (*LT*) and onset of blood lactate accumulation (*OBLA*) obtained during $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$. There were no significant ($P > 0.05$) differences between the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ data

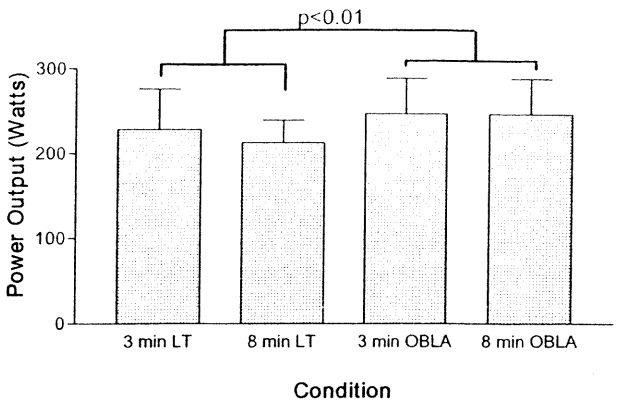

Fig. 3 Power output at the lactate threshold (*LT*) and onset of blood lactate accumulation (*OBLA*) obtained during $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$. There were no significant ($P > 0.05$) differences between the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ data

from two separate incremental exercise tests with step increments of either 3 min ($EXT_{3\text{-min}}$) or 8 min ($EXT_{8\text{-min}}$) duration. Furthermore, we compared the results of these tests in a group of well-trained as opposed to a recreational group of cyclists.

In this study we hypothesized that the prolonged duration of each workload during the $EXT_{8\text{-min}}$ combined with the different abilities of the two groups of cyclists would result in contrasting BLa and $\dot{V}O_2$ measurements at the end of each workload. This in turn would effect the coupled $\dot{V}O_2$ and BLa values at the LT and the OBLA. The results demonstrate that the LT_W of the WT subjects was significantly higher when calculated from the results of the $EXT_{3\text{-min}}$ as compared with the $EXT_{8\text{-min}}$. This finding aside, there were no significant effects of training status (WT or REC) on the $\dot{V}O_2$ or HR at the LT or OBLA obtained from either the $EXT_{3\text{-min}}$ or $EXT_{8\text{-min}}$. Furthermore, there was no significant effect of training status on the $OBLA_W$ obtained from the two different exercise protocols.

BLa is determined by both the production and elimination of lactate (MacRae et al. 1992). During low-intensity exercise lactate is shuttled from the muscle cell and may be eliminated by less metabolically active tissues (Brooks 2000). At the same time oxidative metabolism is preferential at lower work rates, which will result in less production and the possible appearance of lactate in the blood (Jeukendrup et al. 1999). However, during higher intensity exercise greater than the LT, BLa accumulation is more pronounced and continues to rise with prolonged exercise despite a constant work rate (Smith et al. 1998). The ability to reduce muscle lactate production and increase its elimination will dictate the appearance of this metabolite in the blood (Brooks 2000). The WT group of cyclists were superior to the REC group in terms of PPO and $\dot{V}O_2$max. Thus, it is likely that the WT subjects may have had a greater metabolic capacity to reduce BLa accumulation at low and high work rates (Pilegaard et al. 1994). Regardless of training status, during sustained exercise for longer than 3 min, BLa accumulation will more pronounced especially at work rates above the LT (Jones et al.1999). At the same time, it has also been recently shown that training status effects the metabolic response during prolonged exercise above the LT (Baldwin et al. 2000). We have shown that during the $EXT_{8\text{-min}}$ test, when compared to the REC group, the WT subjects had a significantly reduced BLa concentration at low work rates. At higher work rates there was a trend for the BLa concentration to be greater in the REC cyclists, especially in the $EXT_{8\text{-min}}$; however, the BLa concentration remained statistically similar when compared to the WT subjects. Thus, it is likely that the similar BLa response at higher work rates in the $EXT_{8\text{-min}}$ and $EXT_{3\text{-min}}$ in both groups may explain why the W_{OBLA} was statistically similar when calculated from the results of either EXT.

Whilst other reports have detailed changes in ventilation and BLa parameters with different exercise protocols using stages shorter than 5 min (Bishop et al. 1998a; Coen et al. 2000; McLellan 1985; Prioux et al. 1997), to our knowledge, only one previous study has directly investigated the effects on LT and fixed BLa measurements of different exercise protocols using stage durations of less than 3 min and more than 5 min (Weltman et al. 1990). These authors compared the $\dot{V}O_2$, velocity (m/min) and HR values at the LT, and 2.0, 2.5 and 4.0 mM BLa points during incremental treadmill exercise involving either continuous 3-min or discontinuous 10-min workloads. The results showed that the different testing protocols did result in significant effects on the coupled $\dot{V}O_2$ and velocity measurements at the LT or 4 mM BLa point, which is comparable to the present study in terms of the power output and $\dot{V}O_2$ at the OBLA but not the power output at the LT. However, the discontinuous (10-min stage) tests used by Weltman et al. (1990) were conducted

over three separate days, which in turn may have reduced the residual effects of the previously completed workloads that may have been influential in the present study. Furthermore, these authors also used running exercise that may elicit differential metabolic responses than cycling exercise at the same relative exercise intensity (Jones and McConnell 1999). The present study was also able to compare a WT and REC group of athletes during cycle exercise that was controlled in terms of the relative exercise intensity completed during each workload in each test. With this in mind, the results of this study indicate that training status has a limited physiological effect on the OBLA results obtained from a 3-min or 8-min stage incremental exercise test. However, it is possible that the workload at the LT may be influenced by the protocol used to determine this variable in more highly trained subjects. This is especially true as there were no significant effects of the EXT protocol on the LT_W when data from the WT and REC groups were combined.

The purpose of determining the LT and OBLA should be considered when interpreting the significance of the results of this study. Both the LT and OBLA have been used as "predictors" of endurance performance (Sjodin and Svedenhag 1985). Since we did not include a performance test, we are unable to establish whether the differences in the LT or OBLA obtained from the different EXT would reduce or heighten the predictive power of such variables. However, it has been suggested that the change in results obtained from two different incremental exercise tests does not influence the predictive power of the variables assessed (Foxdal et al. 1994). The workload at the OBLA and the LT can also be used to examine the metabolic responses to exercise at these work rates. It is likely that the small but non-significant changes in the workload at the LT or OBLA with the different EXT will effect the physiological responses at these workloads during prolonged exercise. Foxdal et al. (1996) have examined the BLa concentration during 50 min of treadmill exercise at a velocity representing the OBLA calculated from the results of a 4-, 6- or 8-min stage test carried out by a group of either trained runners or firemen. These authors did not directly report the workload at the OBLA; however, the results show contrasting rates of BLa accumulation and time to fatigue during exercise at the different workloads calculated from the different length tests. In the present study no significant differences were found in the W_{OBLA} determined from the $EXT_{8\text{-min}}$ as compared to the $EXT_{3\text{-min}}$. However, it is likely that the small differences that were shown in the $OBLA_W$ may result in contrasting metabolic responses during sustained exercise bouts at these work rates.

An interesting but secondary finding of this study was that $\dot{V}O_2$ was similar in the final minute of both the $EXT_{3\text{-min}}$ and $EXT_{8\text{-min}}$ as well as in the third minute of $EXT_{8\text{-min}}$. It has been suggested that the $\dot{V}O_2$ slow component or a delayed rise in $\dot{V}O_2$ occurs as a result of metabolic acidosis during prolonged exercise (Carter et al. 2000). Indeed, it has been shown that the change in $\dot{V}O_2$ from the third to the seventh minute during six successive incremental work rates is associated with the increase in BLa above the LT (Jones et al. 1999). The results of the present study indicate that the delayed increase in $\dot{V}O_2$ during sustained exercise above the LT did not occur in the WT or REC cyclists that participated in this experiment. However, further studies are required to examine the effects of the magnitude of work rate increment during different exercise modes on the $\dot{V}O_2$ slow component during incremental exercise.

In conclusion, this study compared the workload, $\dot{V}O_2$ and HR at the LT and OBLA determined from the results of incremental exercise tests consisting of workloads of 3 min or 8 min. The results suggest that in contrast to lengthy and sometimes impractical incremental tests incorporating 8- to 10-min stage increments, a 3-min stage test can produce similar results in terms of the OBLA in well-trained or recreational cyclists. However, it is also likely that incremental exercise tests using stage increments longer than 3 min may reduce the workload at the LT in well-trained subjects.

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CHAPTER FIVE

EXPERIMENT TWO

A comparison of the lactate threshold and onset of blood lactate accumulation obtained from two incremental exercise tests in cyclists.

CHAPTER FIVE - EXPERIMENT TWO

5.1 Introduction

The maximum workload or (peak power output- PPO in cycling) obtained from an incremental exercise test to exhaustion has been used as an indicator of endurance ability in time trial cyclists and triathletes (Bentley et al., 1998; Balmer et al., 2000a). The PPO, in combination with the LT and OBLA, also seems to be sensitive to changes in training status with endurance training in elite cyclists (Lucia et al., 2000; Jeukendrup et al., 2000). Of more practical value, the PPO has been used to predict maximal oxygen uptake ($\dot{V}O_2max$) in cycling activity (Hawley and Noakes, 1992). However, the results from experiment one of this research provide evidence that this may not always be the case.

The PPO is defined as the highest work rate completed for a full stage during an incremental exercise test of stage duration between 60-s and 5 min (Paton and Hopkins, 2001). Exercise physiologists working with elite cyclists and measuring the PPO also recommend an incremental exercise test involving stage increments of 60-s duration (Chicharro et al., 2000). However, some studies suggest that $\dot{V}O_2max$ may be compromised when the duration of stages is longer during an incremental exercise test (Bishop et al., 1998a; Pierce et al, 1999). This in turn may affect the relationship between PPO and $\dot{V}O_2max$. Therefore, a general methodological comparison of most studies is the type of incremental exercise protocol used to determine the PPO and in turn $\dot{V}O_2max$.

Two problems exist in the literature concerning the measurement of PPO, the LT and OBLA using incremental exercise tests incorporating a stage duration of 3 to 5 min which are common protocols for measuring these variables (Bentley et al., 1998; Bishop et al., 2000; Padilla et al., 2000). Firstly, does PPO and $\dot{V}O_2$max significantly change during incremental exercise tests comprising stages of 3 min or 5 min duration, thereby changing the LT and OBLA expressed as a percentage of these maximal variables? Secondly, does using an incremental exercise test incorporating 3 min as opposed to 5 min stage duration affect the work rate, $\dot{V}O_2$ and HR corresponding to the LT and OBLA.

In experiment one, two incremental exercise protocols were compared for determining the LT and OBLA. It was shown that the workload (W) corresponding to the LT was significantly lower when the length of stages during an incremental protocol was increased from 3 min to 8 min. However, tests incorporating stage increments of longer (> 5 min) duration are typically submaximal and the PPO can not be quantified. Therefore, it is important to examine whether there is a difference in PPO, LT and OBLA in two tests that enable quantification of *both* the PPO and the LT or the OBLA, thereby reducing the time necessary to complete the measurement of these variables.

Based on the results of experiment one, it is hypothesised that lengthening the stage duration from 3 to 5 min duration will result in a lower LT during incremental cycle exercise in well trained subjects. It is likely that the PPO will be higher when measured from an incremental exercise test using 60-s stage duration as opposed to 3 and 5 min. However, it is not known what effect this may have on the LT and OBLA. It is also not

know to what affect modification of the exercise protocol will have on $\dot{V}O_2max$ together with the LT and OBLA expressed as a % of $\dot{V}O_2max$.

Aims

(5) To determine if the PPO and $\dot{V}O_2max$ are different when measured from an incremental exercise test with stages 60-s, 3 min or 5 min duration.

(6) To establish whether there is a difference in the power output, HR and $\dot{V}O_2$ corresponding to the LT and OBLA obtained via a 3 min or 5 min incremental step test protocol.

5.2 Methodology

5.2.1 Subjects

Ten male cyclists aged 19-34 yrs (mean ± SD age 25.9 ± 5.0 yrs; height 181 ± 5 cm) gave their informed consent to participate in the study. The cyclists were considered to be 'well trained' according to the criteria suggested by Jeukendrup et al. (2000) i.e. $\dot{V}O_2max$ of ~ 60 $ml \cdot kg^{-1} \cdot min^{-1}$; $PPO_{60\text{-}s}$ ~ 400 W. These values are similar to those of the WT trained cyclists who participated in experiment one. The local research ethics committee approved the experimental protocol.

5.2.2 Protocol

Each subject performed three tests on a stationary cycle ergometer (SRM). The first test involved an incremental 'ramp' test to exhaustion using stage increments of 60-s duration ($EXT_{60\text{-}s}$). This test was used to quantify the $\dot{V}O_2max$ and HR_{max}, as well as to quantify workloads used in the 2nd and 3rd tests. The second and third tests consisted of incremental lactate tests involving either 3 min ($EXT_{3\ min}$) or 5 min ($EXT_{5\ min}$) stage increments. The $EXT_{3\ min}$ and $EXT_{5\ min}$ were used to determine the LT and OBLA. All these measurements were expressed in terms of power output (W), $\dot{V}O_2$ as well as HR ($b \cdot min^{-1}$) and relative (%) to $\dot{V}O_2max$, PPO or HR_{max} obtained in each EXT. The PPO ($PPO_{3\ min}$ and $PPO_{5\ min}$) was also established. The remaining two tests were completed in a randomised order. All five tests were completed over a 2-week period with a minimum of 48 hr separating each trial.

5.2.3 Physiological Measurements

Capillary blood samples were collected from an incision made to the earlobe following completion of each workload and at exhaustion during the $EXT_{3\ min}$ and $EXT_{5\ min}$. The blood sample was immediately analysed for lactate (mM) using a laboratory based lactate analyser (YSI-1500 Sport L-lactate analyser, Yellow Springs Instruments, USA). The blood lactate concentration at *fatigue* was measured as the 'blood $lactate_{max}$'. In all incremental tests, expired gases were continuously collected using a breath by breath gas analyser (Cosmed, K4, b^2, Italy) for determination of oxygen consumption ($\dot{V}O_2$), respiratory exchange ratio (RER) and pulmonary ventilation (VE). The breath by breath

data was then averaged every 60-s. The $\dot{V}O_2$max, maximum RER (RER_{max}) and maximum VE (VE_{max}) ($L \cdot min^{-1}$) were established as the highest 60-s average value for each of the variables obtained from each EXT. A portable HR monitor (Polar, Finland) integrated to the power control unit of the SRM system sampled heart rate (HR) every 1-s. HR_{max} was measured as the highest HR value obtained in any stage the EXT. Power output (W) was also continuously collected during each EXT using the SRM crank system. The power output was then averaged for the duration of each workload in the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$. Also, the power output was averaged in the final 60-s, 3 min and 5 min for determination of PPO for each EXT respectively.

The LT was calculated according to Beaver et al. (1985). The OBLA was also interpolated from the curvilinear line and deemed to be the point eliciting a blood lactate concentration of 4 mM (Sjodin and Jacobs, 1981). The power output (W), $\dot{V}O_2$ and HR corresponding to the LT and OBLA were determined in absolute terms or relative to maximal values obtained from each incremental tests (see 'General Materials and Methods').

5.2.4 Statistical analysis

Mean and SD were calculated for each variable obtained from the different tests. The Levene test was used to determine homogeneity of variance. A series of one way ANOVA with Scheffe post-hoc comparisons was used to compare the PPO (W and $W \cdot kg^{-1}$), HR_{max} ($b \cdot min^{-1}$), $\dot{V}O_2$max ($L \cdot min^{-1}$ and $ml \cdot kg^{-1} \cdot min^{-1}$), VE_{max} and RER_{max} and body mass (kg) obtained from each EXT. Single factor (incremental test) ANOVA with

repeated measures was used to compare the power output (W and % PPO), $\dot{V}O_2$ ($L \cdot min^{-1}$ and % $\dot{V}O_2max$) and HR ($b \cdot min^{-1}$) corresponding to the LT and OBLA. Significance was accepted at $p<0.05$.

5.3 Results

5.3.1 Comparison of maximal physiological results

The body mass (kg) of each subject prior to each EXT was statistically similar (Table 5.3.1). There was no significant difference in HR_{max} ($b \cdot min^{-1}$) or VE_{max} ($L \cdot min^{-1}$) when obtained from the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ or $EXT_{5\ min}$ (Table 5.3.1). The RER_{max} was significantly ($p<0.01$) lower in the $EXT_{5\ min}$ as compared with $EXT_{60\text{-}s}$ (Table 5.3.1). The RER_{max} in $EXT_{3\ min}$ was lower than that obtained in $EXT_{60\text{-}s}$ and this result approached statistical significance ($p<0.07$) (Table 5.3.1). The $lactate_{max}$ was not significantly different in the $EXT_{3\ min}$ (7.45 ± 1.57) and $EXT_{5\ min}$ (7.07 ± 1.41). The $PPO_{60\text{-}s}$ was significantly ($p<0.01$) higher than both $PPO_{3\ min}$ and $PPO_{5\ min}$. However, the PPO obtained in the $EXT_{3\ min}$ and $EXT_{5\ min}$ were not significantly different (Figure 5.3.1). PPO ($W \cdot kg^{-1}$) was also significantly ($p<0.01$) higher in the $EXT_{60\text{-}s}$ when compared with $EXT_{3\ min}$ or $EXT_{5\ min}$. The PPO ($W \cdot kg^{-1}$) was slightly higher in $EXT_{3\ min}$ but not significantly different when compared with $EXT_{5\ min}$ (Figure 5.3.2).

Table 5.3.1. Mean (±SD) the maximal physiological variables and body mass obtained from $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$.

	Incremental Exercise Test (EXT)		
	$EXT_{60\text{-}s}$	$EXT_{3\ min}$	$EXT_{5\ min}$
Body mass (kg)	73.1 ± 7.7	72.6 ± 7.2	72.6 ± 7.1
HR_{max} ($b \cdot min^{-1}$)	184.8 ± 10.3	183.3 ± 9.6	180.8 ± 10.2
RER_{max} (abitary units)	1.15 ± 0.09	$1.05 \pm 0.06^{+}$	$1.00 \pm 0.10^{**}$
VE_{max} ($L \cdot min^{-1}$)	181.5 ± 23.9	173.0 ± 22.1	171.4 ± 22.2

Significantly different from $EXT_{60\text{-}s}$ (** $p<0.01$; + $p<0.07$).

Figure 5.3.1. Mean (±SD) peak power output (PPO) (W) measured in the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$.** Significantly ($p<0.01$) different from $EXT_{3\ min}$ and $EXT_{5\ min}$.

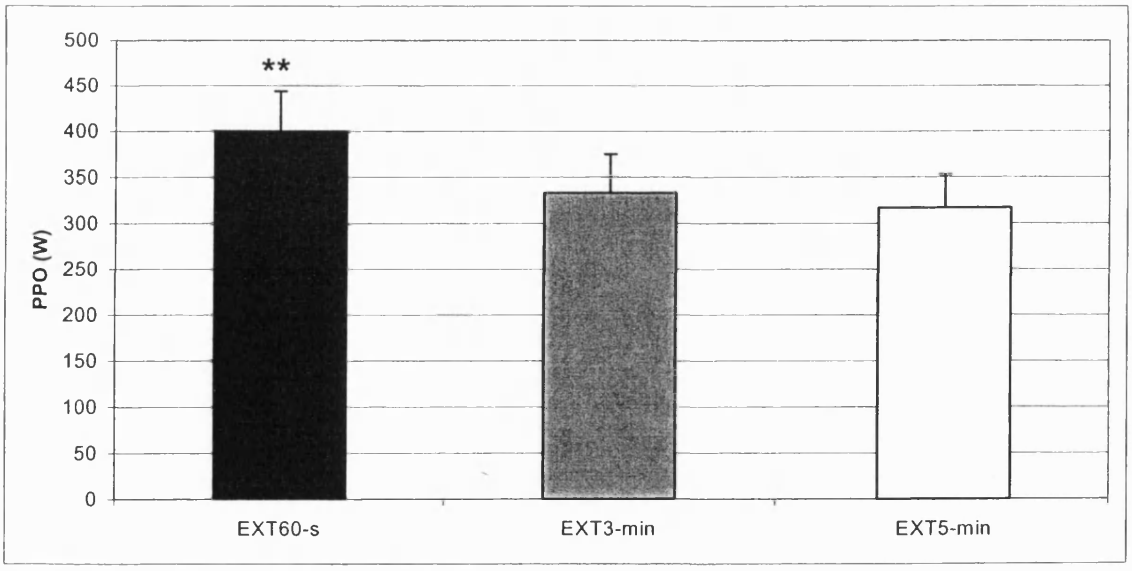
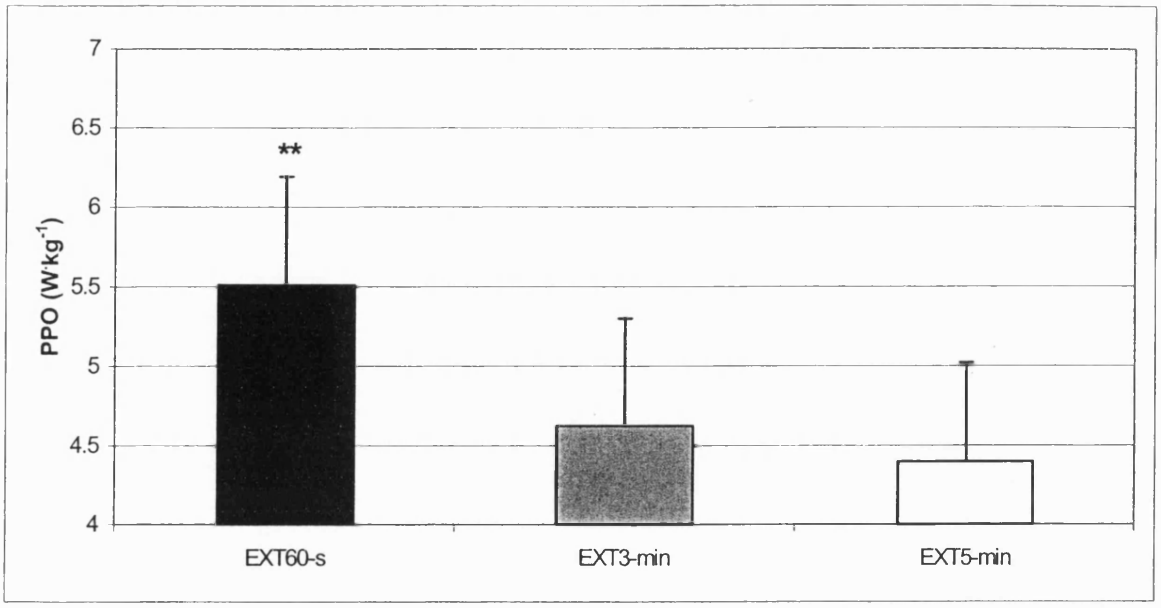


Figure 5.3.2. Mean (±SD) peak power output (PPO) ($W \cdot kg^{-1}$) measured in the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$.** Significantly ($p<0.01$) different from $EXT_{3\ min}$ and $EXT_{5\ min}$.



The $\dot{V}O_2max$ expressed in absolute terms ($ml \cdot min^{-1}$) and relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$) obtained from the $EXT_{60\text{-}s}$ was higher but this value was not statistically different from $EXT_{3\ min}$ or $EXT_{5\ min}$ (Figure 5.3.3 and 5.3.4). There were also no significant differences between $\dot{V}O_2max$ in the $EXT_{3\ min}$ and $EXT_{5\ min}$ (Figure 5.3.3 and 5.3.4).

Figure 5.3.3. Mean (±SD) $\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$) measured in the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$. No significant differences.

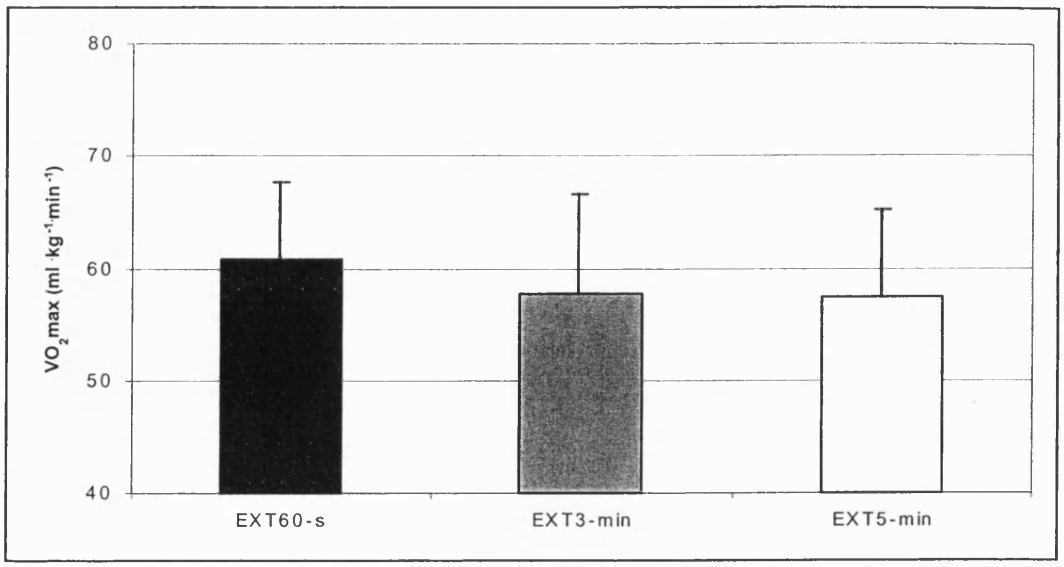
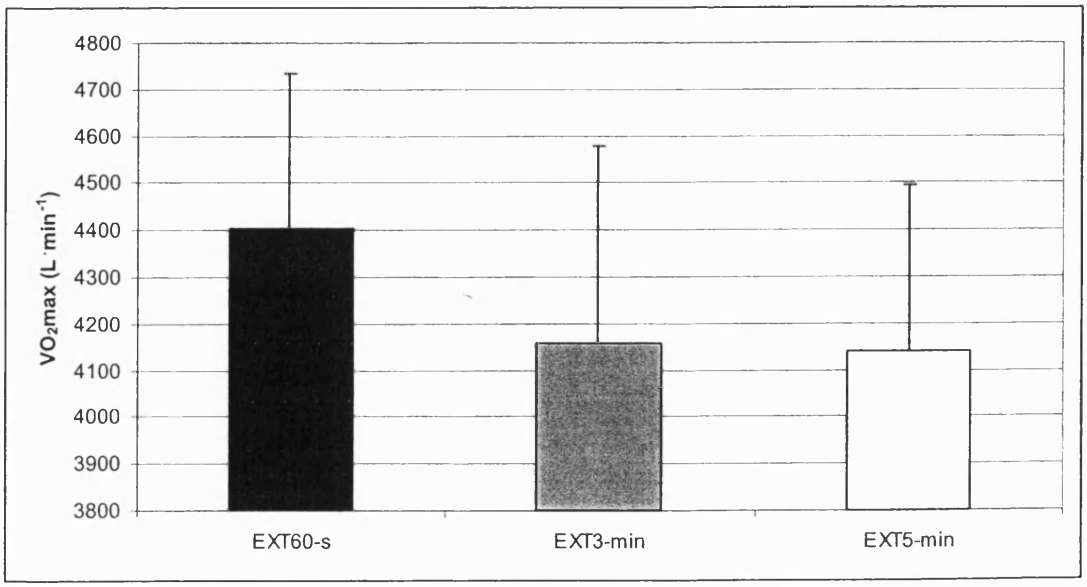


Figure 5.3.4. Mean (±SD) $\dot{V}O_2max$ ($L \cdot min^{-1}$) measured in the $EXT_{60\text{-}s}$, $EXT_{3\ min}$ and $EXT_{5\ min}$. No significant differences.



5.3.2 Comparison of LT and OBLA obtained from $EXT_{3\ min}$ and $EXT_{5\ min}$

Regardless of whether the OBLA was obtained from $EXT_{3\ min}$ or $EXT_{5\ min}$ the power output, $\dot{V}O_2$ and HR corresponding to this variable was always significantly higher than the LT (Figures 5.3.5 to 5.3.7). There was no significant difference in the power output, $\dot{V}O_2$ and HR corresponding to the LT or OBLA when the results of $EXT_{3\ min}$ and $EXT_{5\ min}$ were compared (Figure 5.3.5 to 5.3.7). Similar results were obtained if the power output, $\dot{V}O_2$ or HR was expressed relative to $\dot{V}O_2max$, PPO or HR_{max} measured in the same EXT (Table 5.3.2).

Figure 5.3.5. Mean (±SD) power output (W) corresponding to the LT and OBLA obtained from the $EXT_{3\ min}$ and $EXT_{5\ min}$. ** Significantly ($p<0.01$) different from the LT.

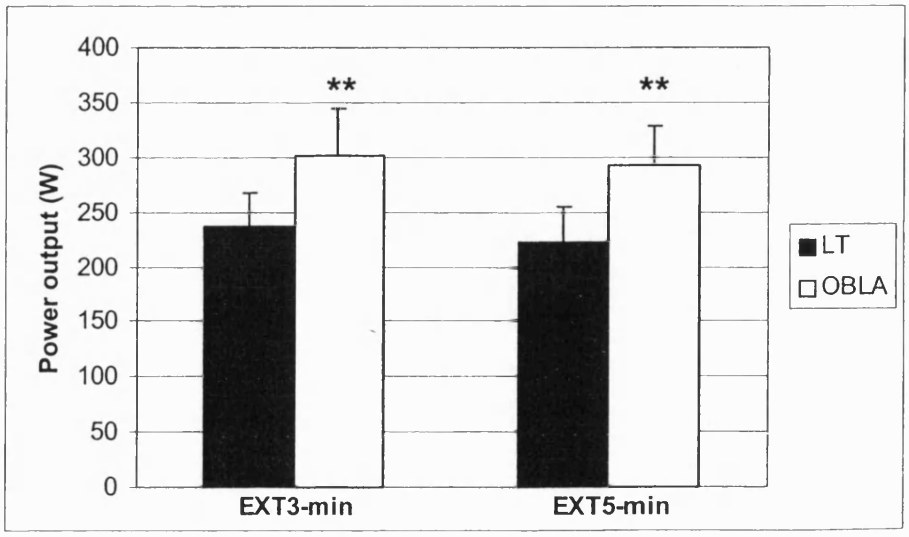


Figure 5.3.6. Mean (±SD) $\dot{V}O_2$ ($L \cdot min^{-1}$) corresponding to the LT and OBLA obtained from the $EXT_{3\ min}$ and $EXT_{5\ min}$. ** Significantly ($p<0.01$) different from the LT.

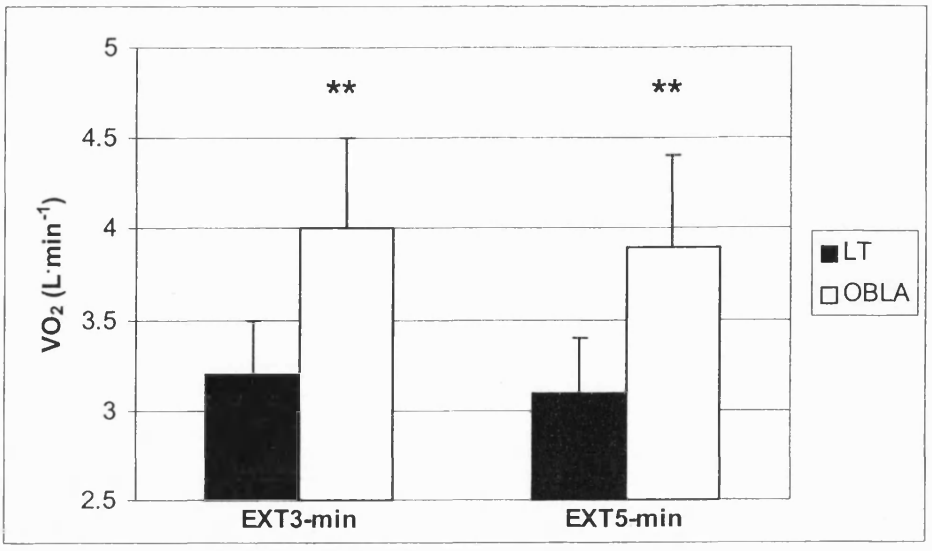


Figure 5.3.7. Mean (±SD) HR ($b \cdot min^{-1}$) corresponding to the LT and OBLA obtained from the $EXT_{3\ min}$ and $EXT_{5\ min}$. ** Significantly ($p<0.01$) different from the LT.

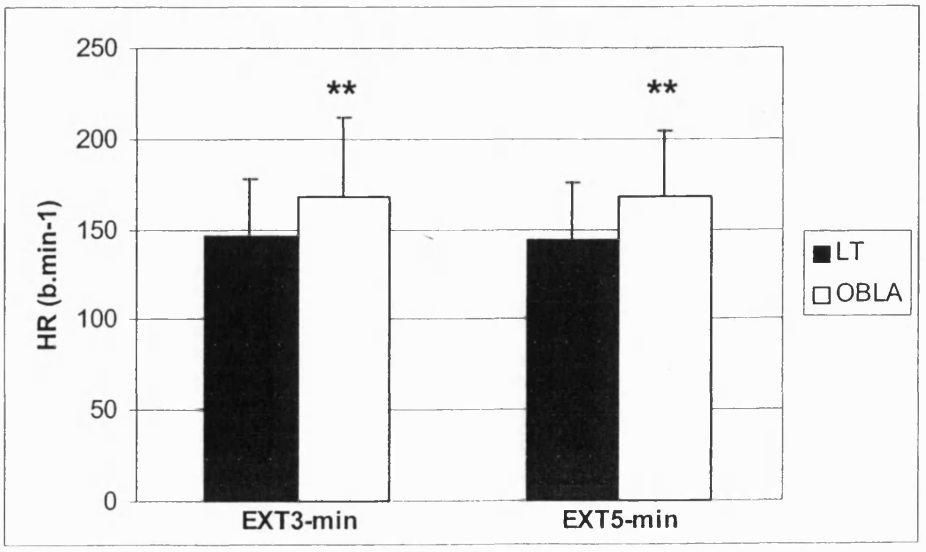


Table 5.3.2. Mean (±SD) power output (%PPO), $\dot{V}O_2$ (% $\dot{V}O_2$max) and HR (%HR_{max}) corresponding to the LT and OBLA obtained from the $EXT_{3\ min}$ and $EXT_{5\ min}$. Different suprascripts^{a,b} indicate significant differences in a column. Different subscripts$_{x,y,z}$ indicate significant differences in a row.

		$EXT_{3\ min}$	$EXT_{5\ min}$
Power Output (%PPO)	LT	$69.7 \pm 5.4^{a}_{x}$	$70.0 \pm 4.4^{a}_{x}$
	OBLA	$88.7 \pm 6.9^{b}_{x}$	$92.1 \pm 4.1^{b}_{x}$
$\dot{V}O_2$ (% $\dot{V}O_2$max)	LT	$77.3 \pm 10.4^{a}_{x}$	$74.7 \pm 5.6^{a}_{x}$
	OBLA	$95.4 \pm 9.3^{b}_{x}$	$93.9 \pm 4.0^{b}_{x}$
HR (%HR_{max})	LT	$79.3 \pm 4.3^{a}_{x}$	$79.6 \pm 4.3^{a}_{x}$
	OBLA	$91.5 \pm 4.7^{b}_{x}$	$93.3 \pm 2.4^{b}_{x}$

5.4 Discussion

This experiment was conducted to examine whether the peak power output (PPO), the LT and OBLA significantly differed when obtained from incremental exercise tests with stages of either 3 or 5 min duration. The results demonstrated no significant difference between the two incremental exercise testing protocols in the power output, $\dot{V}O_2$ or HR corresponding to the LT and OBLA. Furthermore, no significant difference was found for the PPO or $\dot{V}O_2$max between the two incremental tests.

The PPO is used widely to quantify the adaptive response to endurance training, to prescribe endurance training loads, but also to correlate with endurance performance

(Hawley and Noakes, 1992; Weston et al., 1997; Bentley et al., 1998; Lucia et al., 2000; Balmer et al., 2000a). However, all of these studies use contrasting incremental exercise protocols of varied stage duration (between 60-s to 3 min) to establish the PPO. The PPO is measured by obtaining the highest work rate maintained for a set workload duration during an incremental exercise test. However, no clear rational is given by previous authors as to why the specific duration has been selected. At the same time, there is no research that has examined the implications of utilising a particular incremental exercise protocol to establish the PPO. This is especially true when this variable is used to correlate with endurance performance.

Whilst it was expected that the PPO would be higher in the $EXT_{60\text{-}s}$ the data from this experiment demonstrates no significant effects of using a protocol of either 3 or 5 min stage duration to quantify PPO.

Other studies have demonstrated the LT is either significantly reduced or unaffected when the stage duration is increased during incremental exercise (Smith et al., 1997; Yoshida, 1984; Kim et al., 1988). However, these studies were conducted in untrained subjects. This study which used well-trained cyclists as subjects, shows no significant affect of the different incremental exercise protocols on the power output, $\dot{V}O_2$ or HR corresponding to the LT and OBLA.

The choice of stage duration is largely due to the assumption that a period of at least 3 min is required to establish a lactate steady state and in turn increase the validity of blood

lactate measurements during incremental exercise (Thoden, 1991). However, the results of this study demonstrate otherwise, and suggest that either a 3 min or 5 min stage protocol can be used to determine the LT or OBLA in well trained cyclists.

The differences in the LT and OBLA found in other studies using untrained subjects may in part be due to the choice of blood that is used to measure lactate concentrations. It is acknowledged that the choice of blood (venous or arterial or mixed arteriovenous) will influence the level of lactate dissipation thereby resulting in a different lactate concentration at the same workload (Smith et al., 1997; Yoshida, 1984). Applied sport scientists working with endurance athletes generally measure the lactate concentration from mixed arteriovenous blood obtained from the earlobe or finger tip. However, in research situations, more invasive blood sampling procedures are used. Therefore, the type of blood sample obtained and analysed for lactate concentration is a potential confounding factor in these situations (el-Sayed et al., 1993). The blood lactate response to incremental exercise is used to quantify adaptation to endurance training (Lucia et al., 2000). In this regard, it remains to be investigated the affect different blood sampling procedures in combination with lactate diffusion capacity has on the sensitivity of different blood lactate measurements during incremental exercise following a period of endurance training.

The choice of stage duration during incremental exercise ignores the possible implications on measurement of maximal physiological variables such as $\dot{V}O_2$max and PPO. Studies using untrained subjects have shown that the peak $\dot{V}O_2$ value is lower when

the stage duration (and in turn the length of the whole incremental exercise tests), is increased (McLellan, 1985). It has also been suggested that this is due to premature fatigue resulting in the central cardiovascular system not being fully stimulated thereby resulting in a lower $\dot{V}O_2$ value (Bishop et al., 1998a; Pierce et al., 1999). This has two important consequences. Firstly, the $\dot{V}O_2$ value measured may not be a 'true' $\dot{V}O_2max$ figure. Also, submaximal results such as the LT and OBLA expressed as a percentage of $\dot{V}O_2$ (or indeed PPO) may be inflated. However, in support of 2 other studies using trained cyclists and rowers (Bishop et al., 1998a; Pierce et al., 1999), this experiment shows that whilst the $\dot{V}O_2max$ value is lower relative to the results obtained from a shorter 'ramp test', it is not significantly different. Furthermore, the LT and OBLA expressed as a percentage of PPO or $\dot{V}O_2max$ are not significantly affected.

This experiment is the first to compare the LT and OBLA together with the PPO obtained from two incremental exercise tests in a trained group of endurance athletes, who might be expected to demonstrate different physiological adaptations to incremental exercise in comparison to an untrained group. However, similar to what has been shown in sedentary populations (Smith et al., 1998) there were no significant differences in the blood lactate or $\dot{V}O_2$ response to exercise and therefore the LT and OBLA obtained from these tests.

A limitation of this experiment was that blood lactate measurements were not obtained from the $EXT_{60\text{-}s}$. Based on other data, it is possible that the LT may have been higher in an incremental test similar to the $EXT_{60\text{-}s}$ used in this study (McLellan, 1985). At the

same time, the PPO was highest in this test. An incremental exercise test similar to these dimensions has been used by researchers working with cycling to quantify changes in response to endurance training, to distinguish elite from professional cyclists as well as to predict performance (Lucia et al., 1998; Balmer et al., 2000a; Lucia et al., 2000). It is of interest in future studies to examine firstly the differences in the LT and OBLA between an incremental exercise test using 60-s stages and 3 min stages but also to track the changes in these variables together with PPO in response to long term endurance training in well trained cyclists.

The significance of these findings concerns the total length of the incremental tests and therefore the practicality of the incremental tests that was utilised. Generally speaking, each subject was brought to fatigue in ~ 24 min during the $EXT_{3\ min}$. In contrast, fatigue was induced at ~ 40 min in the $EXT_{5\ min}$. Whilst the data from this experiment suggests that from an applied physiological perspective, either incremental exercise test incorporating 3 or 5 min stage duration can be used to the same effect, an incremental test of only 24 min duration could be viewed as having greater practical benefit. An incremental test using 5 min duration could be modified so that fatigue could be induced at ~ 25 min thereby resulting in a similar overall duration. However, this would involve increasing the starting workload together with increasing the magnitude of the stage increment. This in turn may reduce the sensitivity of the submaximal measures such as the LT and OBLA.

In summary, the results of this experiment show that despite an increase in the stage duration from 3 to 5 min during incremental exercise, there were no significant differences in the PPO, LT and OBLA. Therefore, the results of either test can be used by sport scientists for the purpose of quantifying adaptation to endurance training and to predict endurance performance.

CHAPTER SIX

EXPERIMENT THREE

The relationship between peak power output, the lactate threshold, onset of blood lactate accumulation and endurance cycling performance.

Part of this data appears following this chapter

'Bentley, D.J., McNaughton, L.R., Thompson, D., Vleck, V.E. and Batterham, A.M. (2001). Peak power output, the lactate threshold, and time trial performance in cyclists. *Medicine and Science in Sports and Exercise* 33(12): 2077-2081'.

CHAPTER SIX – EXPERIMENT THREE

6.1 Introduction

It has been suggested that endurance events encompass those that are > 20 min in duration (Hawley et al., 1997). Cycling time trials and triathlon events range in duration from 20 min to > 60 min in duration (Bentley et al., 2002; Padilla et al., 2000). The physiological demands of these events may differ because of a variation in both the duration and intensity of these tasks (Padilla et al., 2000). This in turn may affect the relationship between performance in these tasks and the results of incremental exercise testing, such as the LT and OBLA as well as PPO. There is a scarcity of data concerning the relationship between the physiological results of an incremental exercise test e.g. the LT, OBLA and PPO and endurance performance conducted over different intensity and duration. No studies have examined the relationship between PPO, the LT as well as the OBLA and 'short' or 'long' cycle time trial performance in a well-trained population who are also homogeneous in terms of PPO.

The 'performance power' during an endurance event is the average power for the duration of the task, and similarly the 'performance $\dot{V}O_2$' is the average $\dot{V}O_2$ that is maintained for the duration of the event (Coyle, 1995). Both the performance power and $\dot{V}O_2$ are thought to be interrelated and to dictate overall endurance performance (Coyle, 1995). Furthermore, it has also been suggested that these variables are related to the $\dot{V}O_2$ or power output corresponding to the LT (Coyle, 1995; Coyle, 1999). However, the

relationship between the LT, the sustained power output and $\dot{V}O_2$ during a short and long time trial has not been examined.

In experiment two it was shown that the PPO obtained from an incremental test comprising stage duration of 60-s was significantly higher than the PPO obtained from a 3 min stage test. Whilst a number of researchers report data for PPO (60-s or 3-min values) in terms of correlating with cycling performance (Bentley et al., 1998; Balmer et al., 2000a) there are no studies that have examined the relationship between the PPO obtained from the two different incremental exercise protocols and endurance performance.

Aims

(1) Determine the relationship between the LT, the OBLA cycling time trial performance of long (90 min) and short (20 min) duration.
(2) Determine the relationship between PPO obtained from both $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ as well as cycle time trial performance of short or long duration in well trained endurance athletes.
(3) Determine the relationship between the LT and the OBLA as well as the sustained power output ('performance power') and $\dot{V}O_2$ ('performance $\dot{V}O_2$') during a long and short cycling time trial.

6.2 Methodology

6.2.1 Subjects

Nine male cyclists and triathletes mean ± SD age 32 ± 3 yr.; body mass 77.3 ± 4.8 kg and height 185.5 ± 3.3 cm] participated in the experiment. At the time of recruitment, each subject was competing in cycling time trials or triathlon events that consisted of a cycle stage of between 20 and 90-km. Whilst the subjects were not elite, they fulfilled criteria for inclusion in the study of a $\dot{V}O_2$max of > 60 and <70 ml·kg·min^{-1}. Therefore, these subjects were similar in terms of $\dot{V}O_2$max to the WT subjects in experiment one as well as the subjects in experiment two.

6.2.2 Procedures

Each subject was required to complete four tests performed on an SRM cycle ergometer (Schroberer Rad MeBtechnik, Weldorf, Germany) over a two week period. The cycle ergometer was adjusted to the subject's own requirements and fitted with clipless pedals. The reliability and manufacturing specifications of this ergometer have been reported elsewhere (Jones and Passfield, 1998). Each of the four tests was separated by at least 24 hrs. The testing comprised (1) a continuous incremental 'ramp' test ($EXT_{60\text{-}s}$) for determination of PPO ($PPO_{60\text{-}s}$), $\dot{V}O_2$max (ml·min^{-1} and ml·kg^{-1}·min^{-1}) and maximum heart rate (HR_{max}) (b·min^{-1}); (2) a continuous incremental lactate test ($EXT_{3\ min}$) to determine the peak power output ($PPO_{3\ min}$), the LT and OBLA (See 'General Materials and Methods'); (3) a 20 min TT; and (4) a 90 min TT.

During the 90 min TT expired gases were collected breath-by-breath in the first and final 2 min of exercise as well as for a 2 min period at 10, 20, 40, 60 and 80 min throughout the trial. During the 20 min TT expired gases were collected throughout the entire trial. The expired gas samples were averaged (every 2 min during 20 min and for the 2 min duration at each time point during the 90 min TT) for determination of $\dot{V}O_2$. The average $\dot{V}O_2$ for the entire trial was expressed as a % of $\dot{V}O_2$max obtained in the ramp test. Power output (W) and HR ($b \cdot min^{-1}$) data were collected at 1-s intervals throughout the trial using the power control unit of the SRM cycle ergometer. The data was then averaged for 2 min periods corresponding to when the gas data was collected. The power output and HR was averaged and expressed in absolute terms and as a % of PPO obtained in the $EXT_{3\text{-}min}$ and HRmax respectively. The power output and HR were also averaged for the entire trial period.

6.2.3 Statistical analyses

Mean (±SD) were calculated for each physiological variable obtained in the $EXT_{60\text{-}s}$ and $EXT_{3\ min.}$ The average $\dot{V}O_2$, power output and HR were also calculated from the 90 min and 20 min TT. Students t-test for paired samples were used to compare the overall physiological results of the 20 min and 90 min TT. An additional students t-test was used to compare the $PPO_{60\text{-}s}$ and $PPO_{3\ min}$. Pearson's product correlations were calculated to examine the relationship between the physiological variables obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ as well as each physiological variable obtained during the 20 min and 90 min time trials. Significance was accepted at $p<0.05$.

6.3 Results

6.3.1 Physiological attributes of the participating subjects

The mean (±SD) $\dot{V}O_2$max (absolute and relative to body mass) of the cyclists was 4.85 ± 0.3 l·min^{-1} and 62.7 ± 4.8 ml·kg^{-1}·min^{-1} respectively. The PPO (W) obtained from the $EXT_{3\ min}$ (358.3 ± 15.6) was significantly ($p<0.01$) lower than the same variable obtained from the $EXT_{60\text{-}s}$ (425.9 ± 24.1). These variables were also not significantly correlated ($r=0.60$; $p=0.09$). The subjects possessed a HR_{max} of 178.3 ± 6.5 b·min^{-1}. There were significant ($p<0.05$) differences in the OBLA in terms of both power output (W) and $\dot{V}O_2$ when compared with LT (Figure 6.3.1 and 6.3.2). The HR (b·min^{-1}) corresponding to the OBLA was also significantly higher than the HR corresponding to the LT (Figure 6.3.3). The OBLA (%PPO) was significantly ($p<0.01$) higher than the LT (Table 6.3.1). The OBLA was also significantly ($p<0.05$) higher than the LT when expressed relative to $\dot{V}O_2$max and HR_{max} obtained from the $EXT_{60\text{-}s}$ (Table 6.3.1).

Table 6.3.1. The mean (±SD) LT and OBLA expressed relative to $PPO_{3\ min}$, $\dot{V}O_2$max and HRmax obtained from $EXT_{60\text{-}s}$.

	% $PPO_{3\ min}$	% $\dot{V}O_2$max	% HRmax
LT	$68.8 \pm 8.0_x^a$	$67.8 \pm 9.3_x^a$	$79.5 \pm 4.8_x^b$
OBLA	$79.7 \pm 7.7_y^a$	$76.6 \pm 10.2_y^a$	$86.7 \pm 5.5_y^b$

Different subscripts indicate a significant difference in a column.

Different suprascripts indicate a significant difference in a row.

Figure 6.3.1. The mean (±SD) power output (W) corresponding to the LT and OBLA expressed in absolute terms. ** $p<0.01$

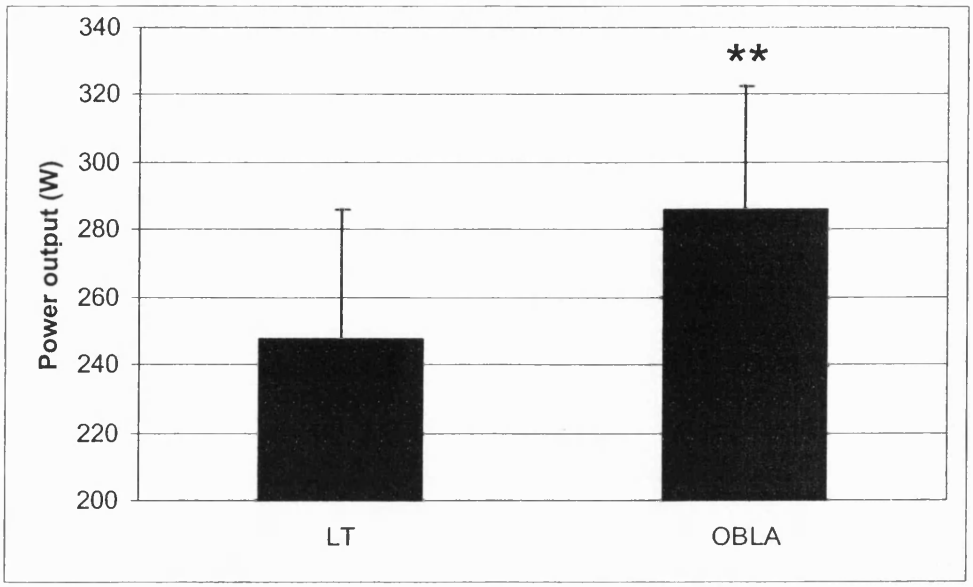


Figure 6.3.2. The mean (±SD) $\dot{V}O_2$ ($ml \cdot min^{-1}$) corresponding to the LT and OBLA expressed in absolute terms. ** $p<0.05$

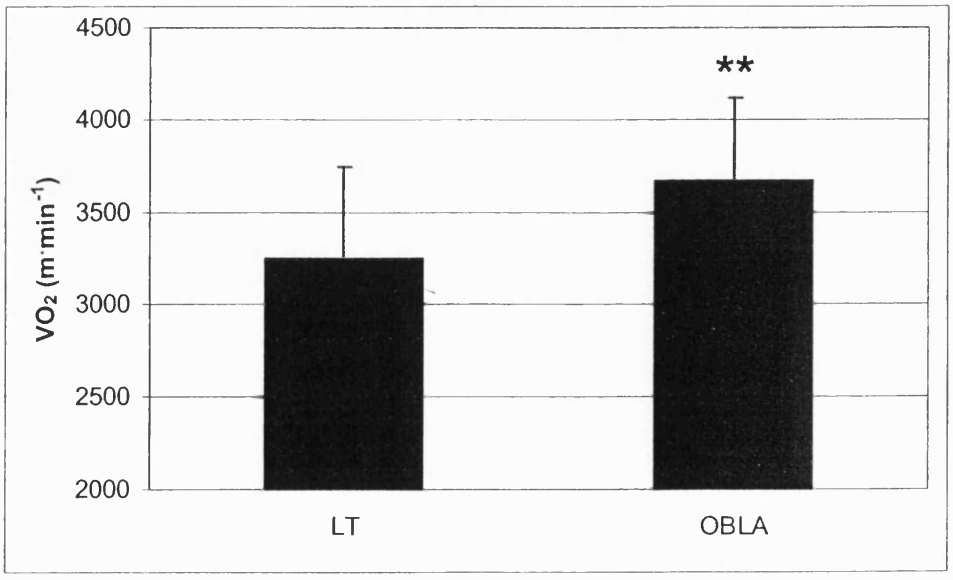
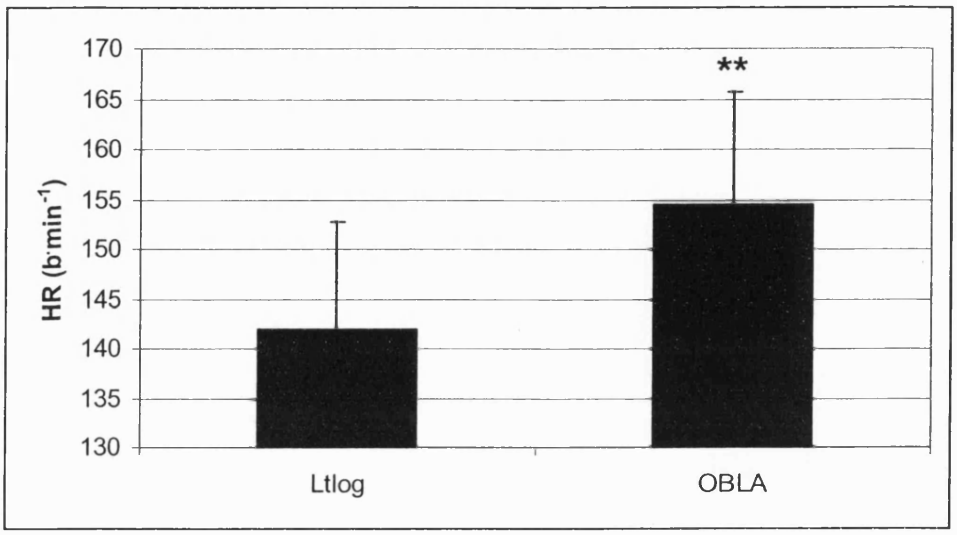


Figure 6.3.3. The mean (±SD) heart rate ($b \cdot min^{-1}$) corresponding to the LT and OBLA expressed in absolute terms. **P<0.01



6.3.2 Physiological responses during the 20 min and 90 min TT

The average power output (W) in the 20 min TT was significantly ($p<0.01$) higher than in the 90 min TT (323.7 ± 17.2 vs. 284.3 ± 8.6). Also, the average $\dot{V}O_2$ ($ml \cdot min^{-1}$) in the 20 min TT was significantly ($p<0.01$) higher than in the 90 min TT (4421 ± 217 vs. 3903 ± 313 $ml \cdot min^{-1}$). In addition, the average HR ($b \cdot min^{-1}$) during the 20 min (169.1 ± 8.0) and 90 min TT (156.3 ± 6.9) was significantly ($p<0.01$) different. There were weak correlations between the average power output (W) ($r=0.66$; $p<0.06$) and HR ($b \cdot min^{-1}$) ($r=0.64$; $p<0.07$) in the 20 min and 90 min TT. However, the average $\dot{V}O_2$ ($ml \cdot min^{-1}$) ($r=-0.03$) during the two TT were not significantly correlated. The overall power output (expressed as a % $PPO_{3\ min}$) was significantly ($p<0.01$) higher in the 20 min than in the 90 min TT (Figure 6.3.4 and Table 6.3.2). The $\dot{V}O_2$ and HR expressed relative (%) to $\dot{V}O_2max$ and HR_{max} were also significantly higher ($p<0.01$) in the 20 min vs. the 90 min TT (Figure 6.3.5 and 6.3.6, Table 6.3.2). As with the absolute values, there were no significant correlations between the average power output (%$PPO_{3\ min}$) ($r=0.51$); $\dot{V}O_2$ (% $\dot{V}O_2max$) ($r=-0.01$) and HR (%HR_{max}) ($r=0.59$) in the 20 min and 90 min TT.

Table 6.3.2. The overall average PO (%PPO), $\dot{V}O_2$ (%$\dot{V}O_2$max) and HR (%HR_{max}) during the 90 min and 20 min TT.

	20 min	90 min
PO (%PPO)	90.4 ± 4.2	79.4 ± 1.5**
$\dot{V}O_2$ (%$\dot{V}O_2$max)	91.7 ± 5.9	79.5 ± 8.2**
HR (%HR_{max})	94.9 ± 4.2	87.7 ± 3.5**

** Significantly ($p<0.01$) different from 20 min

Figure 6.3.4. The mean (±SD) power output (% PPO) during the course of the 20 min and 90 min time trials.

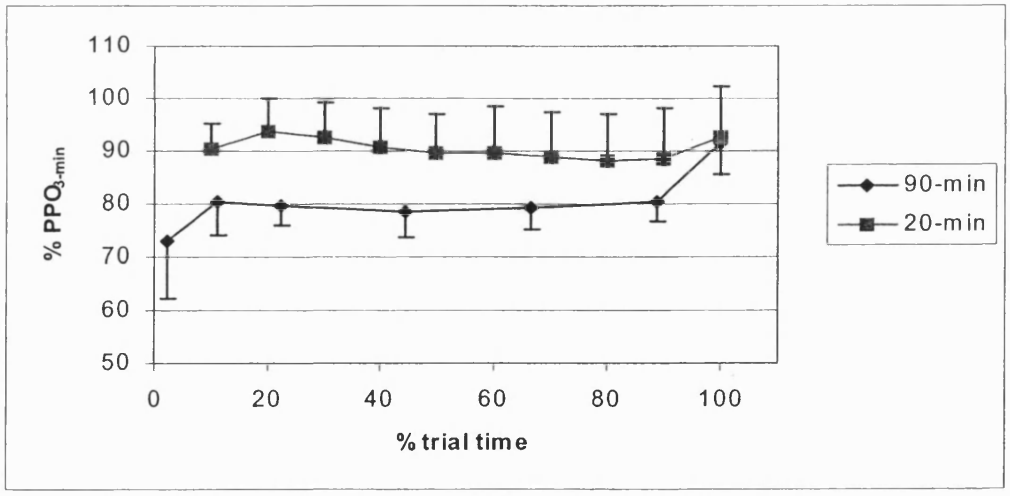


Figure 6.3.5. The mean (±SD) $\dot{V}O_2$ (%$\dot{V}O_2$max) during the course of the 20 min and 90 min time trials.

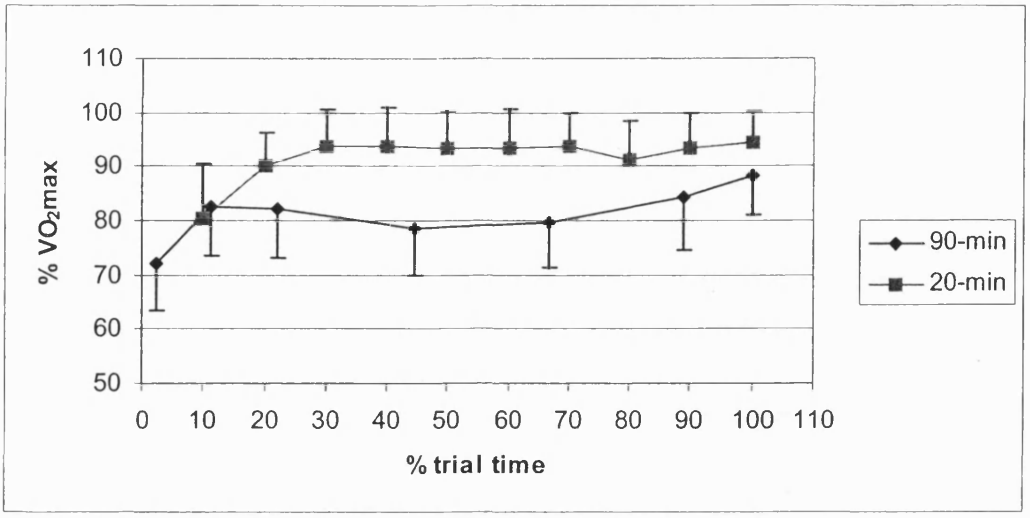
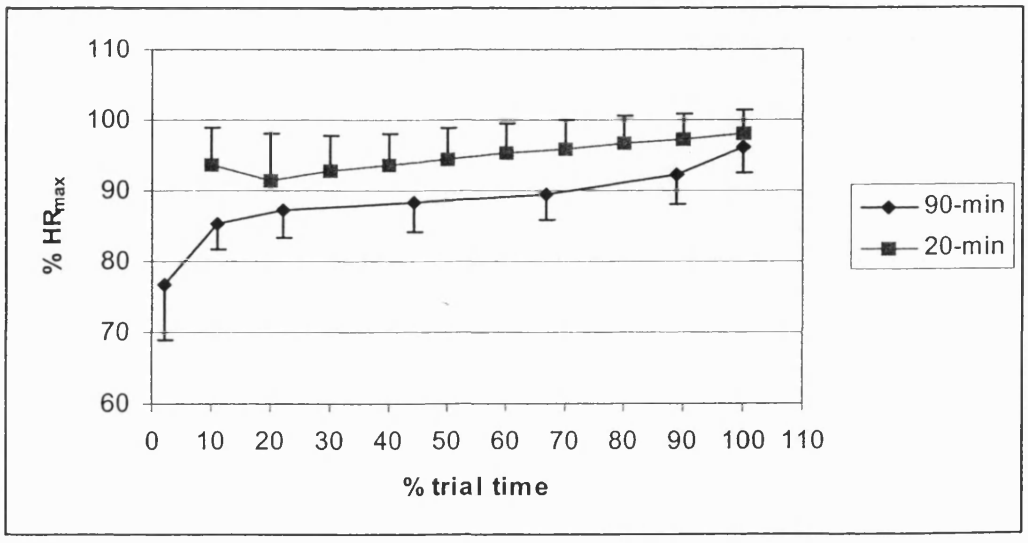


Figure 6.3.6. The mean (±SD) HR during the 20 min and 90 min expressed as a % of HR_{max}.



6.3.3 The relationship between PPO, $\dot{V}O_2$max sustained power output and $\dot{V}O_2$ during the cycling time trials.

No significant correlation was found between $\dot{V}O_2$max ($ml \cdot kg^{-1} \cdot min^{-1}$) and the average power output (W) or $\dot{V}O_2$ in either the 20 min or 90 min TT. However, $\dot{V}O_2$max ($L \cdot min^{-1}$) was significantly correlated to the average power output (W) during the 20 min TT ($r=0.69$; $p<0.05$) but not during the 90 min TT ($r=0.38$). There were no significant correlations between $\dot{V}O_2$max ($ml \cdot min^{-1}$) and the average power output ($\%PPO_{3\ min}$) in the 20 min or 90 min TT. There was a weak correlation ($r=-0.66$; $p<0.06$) between $\dot{V}O_2$max ($l \cdot min^{-1}$) and the $\%\dot{V}O_2$max sustained during the 20 min TT. There was no significant correlation between $\dot{V}O_2$max ($l \cdot min^{-1}$) and the sustained $\dot{V}O_2$ during the 90 min TT.

The $PPO_{3\ min}$ was highly correlated ($r=0.91$; $p<0.01$) to the average power output (W) during the 90 min TT. Interestingly, there was an inverse relationship ($r=-0.80$; $p<0.01$) between $PPO_{3\ min}$ and the average power output ($\%PPO_{3\ min}$) during the 90 min TT. There was no significant correlation between $PPO_{3\ min}$ and the average power output (W or $\%PPO_{3\ min}$) during the 20 min TT. There was also no significant correlation between $PPO_{3\ min}$ and the average $\dot{V}O_2$ during both time trials. In contrast to the $PPO_{3\ min}$, there was no significant correlation between the $PPO_{60\text{-}s}$ and the average power output (W) in 20 min ($r=0.46$) or 90 min TT ($r=0.51$).

Table 6.3.3. Correlation (r) between $\dot{V}O_2max$ obtained in the $EXT_{60\text{-}s}$, $PPO_{3\ min}$ and $PPO_{60\text{-}s}$ as well as the average power output in the 20 min and 90 min time trials expressed in absolute (W) terms and relative (%) to $PPO_{3\ min}$.

	20 min		90 min	
	W	%PPO	W	%PPO
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.47	0.33	0.11	-0.31
$\dot{V}O_2max$ ($ml \cdot min^{-1}$)	0.69*	0.34	0.38	-0.53
$PPO_{3\ min}$ (W)	0.54	-0.31	0.91**	-0.80**
$PPO_{60\text{-}s}$ (W)	0.46	-0.03	0.51	-0.53

* $p<0.05$ ** $p<0.01$

Figure 6.3.7. The relationship between power output ($PPO_{3\ min}$) and the average power output during the 90 min time trial.

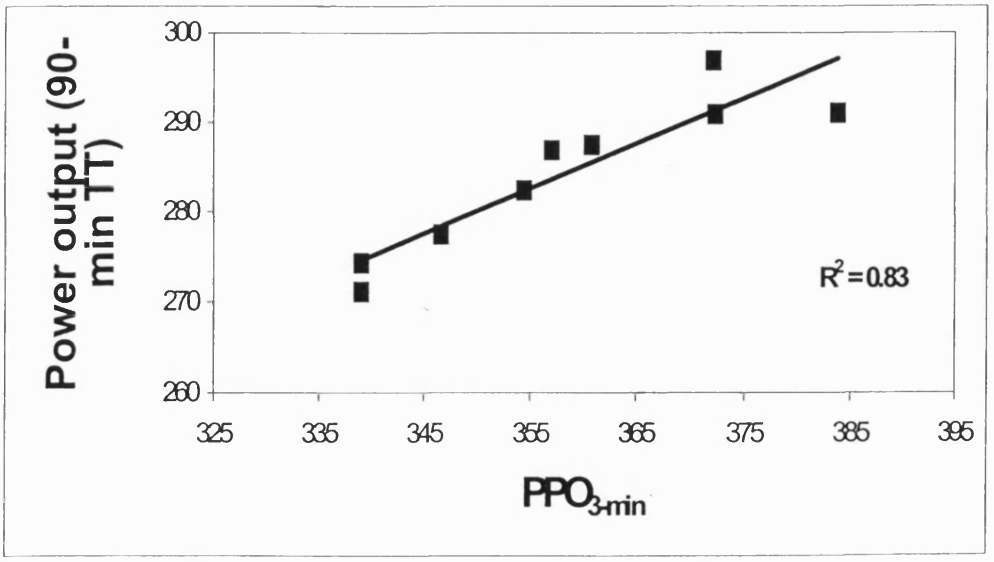


Table 6.3.4. Correlation (r) between $\dot{V}O_2max$ in the $EXT_{60\text{-}s}$, the $PPO_{3\ min}$ and $PPO_{60\text{-}s}$ as well as the average $\dot{V}O_2$ in the 20 min and 90 min time trials expressed in absolute ($ml \cdot min^{-1}$) terms and relative (%) to $\dot{V}O_2max$.

	20 min		90 min	
	$ml \cdot min^{-1}$	$\% \dot{V}O_2max$	$ml \cdot min^{-1}$	$\% \dot{V}O_2max$
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.11	-0.36	-0.05	-0.10
$\dot{V}O_2max$ ($ml \cdot min^{-1}$)	0.10	-0.66+	0.18	-0.28
$PPO_{3\ min}$ (W)	0.46	-0.01	0.58	0.03
$PPO_{60\text{-}s}$ (W)	-0.04	-0.52	0.29	-0.13

+ $p<0.06$

6.3.4 Relationship between the LT, OBLA and cycle time trial performance

Table 6.3.5. Correlation coefficients between the power output (W and $\%PPO_{3\ min}$) corresponding to the LT and OBLA and the average power output (W and $\%PPO_{3\ min}$) during the 20 min and 90 min TT.

	20 min		90 min	
	W	%PPO	W	%PPO
LT (W)	0.67*	-0.05	0.91**	-0.51
LT ($\%PPO_{3\ min}$)	0.66+	0.04	0.85**	-0.37
OBLA (W)	0.23	-0.22	0.54	-0.31
OBLA ($\%PPO_{3\ min}$)	0.02	-0.13	0.23	-0.29

+ $p<0.06$. * $p<0.05$ ** $p<0.01$

The data indicated that the LT (W) was significantly correlated to the average power output that was sustained during the 90 min TT (Table 6.3.5). Also, the LT (%$PPO_{3\ min}$) was significantly correlated to the average power output (W) during the 90 min TT. The LT (W) was the only variable that was significantly correlated to the average power output (W) during the 20 min TT ($r=0.67$; $p<0.05$). The OBLA (W and %$PPO_{3\ min}$) was not significantly correlated to the average sustained power output in either the 20 min or 90 min TT. In contrast, to the average sustained power output in absolute terms (W), there was no significant correlation between the LT as well as the OBLA and the average power output expressed as a % of $PPO_{3\ min}$ in either the 20 min or 90 min TT.

In marked contrast to the power output measurements, there were no significant correlations between the $\dot{V}O_2$ corresponding to the LT or OBLA (expressed in absolute terms or relative to $\dot{V}O_2max$) and the sustained $\dot{V}O_2$ during either the 20 min or 90 min TT (Table 6.3.6)

Table 6.3.6. Correlation coefficients between the $\dot{V}O_2$ ($ml \cdot min^{-1}$ and $\%\dot{V}O_2max$) corresponding to the LT and OBLA and the average $\dot{V}O_2$ ($ml \cdot min^{-1}$ and $\%\dot{V}O_2max$) during the 20 min and 90 min TT.

	20 min		90 min	
	$ml \cdot min^{-1}$	$\%\dot{V}O_2max$	$ml \cdot min^{-1}$	$\%\dot{V}O_2max$
LT ($ml \cdot min^{-1}$)	0.48	0.22	-0.05	-0.51
LT ($\%\dot{V}O_2max$)	0.41	0.41	0.01	-0.38
OBLA ($ml \cdot min^{-1}$)	-0.19	-0.02	-0.07	-0.32
OBLA ($\%\dot{V}O_2max$)	-0.24	0.17	0.01	-0.10

Table 6.3.7. Correlation coefficients between the HR ($b \cdot min^{-1}$ and $\%HR_{max}$) corresponding to the LT and OBLA and the average HR ($b \cdot min^{-1}$ and $\%HR_{max}$) during the 20 min and 90 min TT.

	20 min		90 min	
	$b \cdot min^{-1}$	$\%HR_{max}$	$b \cdot min^{-1}$	$\%HR_{max}$
LT ($b \cdot min^{-1}$)	0.07	-0.43	0.33	-0.19
LT ($\%HR_{max}$)	-0.20	-0.37	0.11	-0.04
OBLA ($b \cdot min^{-1}$)	0.09	-0.26	-0.17	-0.58
OBLA ($\%HR_{max}$)	-0.18	-0.13	-0.48	-0.45

6.4 Discussion

This experiment was conducted to examine the relationship between PPO, the LT as well as the OBLA and the performance power and $\dot{V}O_2$ (Coyle, 1995) during a cycle time trial of duration 20 min or 90 min. The results demonstrate that the average power output during the 90 min TT was highly correlated to the PPO obtained from the $EXT_{3\ min}$. The average power output during the 90 min trial was also correlated to the LT expressed in absolute terms (W) or relative to $PPO_{3\ min}$. In contrast, the average power output in the 20 min TT performance was only moderately correlated to $\dot{V}O_2max$ ($ml \cdot min^{-1}$) and the LT (W). Interestingly, 20 min time trial performance was not correlated to 90 min TT performance. Furthermore, the $\dot{V}O_2$ corresponding to the LT and OBLA did not correlate with the average $\dot{V}O_2$ during either of the 20 min or 90 min time trials.

The PPO together with $\dot{V}O_2max$ are used widely to quantify the adaptive response to endurance training, to prescribe endurance training loads, but also to correlate with endurance performance (Hawley and Noakes, 1992; Weston et al., 1997; Bentley et al., 1998; Lucia et al., 2000; Balmer et al., 2000a). The PPO is measured by obtaining the highest work rate maintained for a set duration during an incremental exercise test. All of these studies use contrasting incremental exercise protocols of varied stage duration (between 60-s to 3 min) to establish the PPO. This study has extended previous investigations by examining the relationship between the PPO obtained in a ramp style test and the PPO in a longer 3 min stage test, as well as the average power output during a long and short endurance task. The results of this study show a significant decrement in

PPO when measured from an $EXT_{3\ min}$ as opposed to $EXT_{60\text{-}s}$. However, in the present study 83% of the variation in the average power output (W) during the 90 min TT was explained by $PPO_{3\ min}$, but only 29% for the same variable in the 20 min TT. In contrast, no significant correlation was found for the $PPO_{60\text{-}s}$ and the average power output in either the 20 min or 90 min TT.

It is interesting to examine the results of other studies that have examined the relationship between PPO and endurance performance. In this experiment a highly significant correlation coefficient of ($r=0.91$) was found for $PPO_{3\ min}$ and the average power output generated during a 90 min TT. In comparison, Hawley and Noakes (1992) reported a correlation of $r=-0.91$ ($p<0.01$) between the PPO and 20-km cycle time trial performance (measured in minutes needed to complete the trial) which is similar to that found in this experiment. However, these authors used an incremental exercise protocol of 2.5 min stage duration commencing at a workload of 3.3 W·kg. Therefore, the starting workload was much higher thereby reducing the overall length of the test to ~ 15 min which is of similar duration to the $EXT_{60\text{-}s}$ used in this study. However, the subjects in that study were of greater number and also of mixed ability level and this may have influenced the results. In another experiment Bentley et al. (1998) found the PPO measured from an incremental exercise test using stages of 3 min duration was highly correlated ($r=-0.87$; $p<0.01$) to the duration of a 40 km cycle stage of a triathlon event. However, in that study the subjects were of also of mixed ability level and this may have inflated the correlation coefficient. At the same time both performance trials were conducted in the field. In another longitudinal study a highly significant correlation ($r=-0.91$; $p<0.01$) was found

between PPO (obtained from a similar protocol to that used by Hawley and Noakes, 1992) and the time taken to complete a 40-km TT in well-trained cyclists (Weston et al., 1997). Another experiment has reported the PPO obtained during an incremental exercise test comprising 60-s stage duration is related to the average power output during a cycle time trial over a distance of 16.1-km (r = 0.99) (Balmer et al., 2000a). Therefore, it is likely based on the results of this study, that the incremental exercise protocol used to determine PPO together with performance measure (i.e. average speed, power output or elapsed time) may influence the relationship between these sets of variables. At the same time, it is also possible that the homogenous nature of the group used in this study may have also lead to the conflicting results in terms of the correlation between PPO and endurance performance. Further work is needed to examine the reliability and validity of PPO obtained during different incremental exercise protocols and the relationship to endurance performance differing by mode and duration.

Coyle (1995) suggests that the 'performance power' together with the 'performance $\dot{V}O_2$' during an endurance event is dictated by such factors as skeletal muscle oxidative capacity, the LT and exercise economy. It is common for the workload associated with set lactate values (i.e. the OBLA), inflection points or other mathematical models such as the Dmax lactate threshold to be used to assess endurance performance (Bishop et al., 1998b). The results of this experiment demonstrate that power output (W) corresponding to the LT was correlated to both 20 min and 90 min TT performances. However, only 45 % of the variation in the average power output (W) during the 20 min TT was explained

by the LT (W) in contrast to 83 % for the same variable in the 90 min TT. The OBLA was not related to either 20 min or 90 min time trial performance.

Theoretically, athletes with an elevated power output at the LT may exercise at a higher work rate without accumulation of blood lactate than athletes with a lower power output at the LT. The LT is also known to be related to muscle oxidative capacity (Ivy et al., 1980) and this is thought to be one factor that positively influences FFA metabolism during prolonged submaximal exercise (Coggan et al., 1992; Coyle et al., 1988). This may delay power output decrement during cycling by limiting glycogen depletion by preferential use of fat related substrates (Klein et al., 1994). Therefore, it is likely that these characteristics associated with the LT partly explained the high correlation of this variable to power output generated during the 90 min TT. However, the fact that only 45% of the variation in the power output during the 20 min TT was explained by the LT seems to indicate that other factors aside from the ability to delay lactate accumulation during incremental exercise may reflect 'shorter' distance TT performance.

In contrast to other investigations (Bishop et al., 1998b; Sjodin and Jacobs, 1981), the present results show that the OBLA was not related to either the average power output during the 20 min or 90 min time trials. One difficulty that has been reported in using the workload at set blood lactate concentrations is the extreme variability in lactate diffusion from muscle into the blood (MacRae et al., 1992). Other factors associated with lactate transportation and elimination from the exercising muscle may influence the blood lactate concentration during incremental exercise (Brooks, 2000). Therefore, it is possible the

OBLA may not be a reflection of the muscle metabolic stress that occurred at the workload eliciting the set lactate concentrations. At the same time, whilst the LT is thought to be related to skeletal muscle oxidative capacity (Ivy et al., 1980; Coyle, 1995), it is possible that this is not evident in regards to the OBLA. Bishop et al. (2000) has reported that the extent of muscle capillarisation around type II muscle fibres is related to the submaximal markers obtained from an incremental exercise test. Weston et al. (1997) have also shown that skeletal muscle buffering capacity is correlated to 60 min TT performance. Other studies are required to examine what characteristics in skeletal muscle are associated with the LT and OBLA (together with the PPO). At the same time, other research is required to examine the relationship between selected morphological characteristics and short to long distance endurance performance in the laboratory and in the field.

The average power output sustained by the cyclists in this experiment during the 90 min time trial was not related to the average power output during the 20 min time trial. As exercise intensity increases above the LT the utilisation of glycogen for energy metabolism is elevated (Vollestad and Blom, 1985). The average power output during the 20 min TT approximated 90% of $PPO_{3\ min}$, which is higher than the power output at the LT. The power output during the 90 min time trial was similar to that corresponding to the LT. Therefore, it is likely that accumulation of lactic acid was much greater during the 20- min TT than in the 90 min TT. Thus, power output decrement during the shorter duration TT may have been influenced to a greater extent by metabolic acidosis rather than substrate depletion. In contrast to shorter duration endurance exercise, previous

studies have also shown that during endurance exercise lasting more than 60 min the utilisation of FFA and triglycerides increases (Kiens et al., 1993; Klein et al., 1994). It is also well known that endurance training enhances the capacity of skeletal muscle to utilise FFA thus delaying the reduction in work output as a consequence of glycogen depletion (Holloszy and Coyle, 1984). From the data presented in these studies, it is possible that substrate depletion may have been more influential during the 90 min TT as opposed to a disruption of the contraction process by metabolic acidosis (Andrews et al., 1996) during the 20 min TT. This aside, other studies have quantified the exercise intensity during cycle time trials in using heart rate coupled with incremental exercise test results (Padilla et al., 2000). These studies suggest that elite cyclists spend a greater portion of the exercise time above the LT in time trials lasting 60 min which would result in substantial accumulation of blood lactate. The findings of the present experiment suggest that physiological factors such as heightened acid base balance or efficient substrate metabolism for energy provision maybe more influential during the 20 min or 90 min TT respectively. It is also very likely that the ability level of the cyclists being tested will affect the metabolic response to a 20 min and 90 min time trial.

The endurance tasks performed by the cyclists in this experiment are similar to other variations that have been validated before and used to examine the effect of dietary modification (Jeukendrup et al., 1996; Burke et al., 2000). However, because the results of these time trials were collected within the laboratory, the results are only likely to be applicable in this situation. The relevance of these results in a field setting may be limited. Indeed, it has been recently reported that the relationship between maximum

workload (PPO) and time trial performance is reduced when the time taken to complete a set distance is utilised (Balmer et al., 2000a). That being said, the primary objective was to examine the 'performance power' and 'performance $\dot{V}O_2$' and the physiological parameters correlated to these. Therefore, this objective was clearly achieved. At the same time, the 20 min time trial used in this study is equivalent to ~ 20-25 km time trial in field depending upon ability level (Hawley and Noakes, 1992). Other researchers have reported a high correlation between PPO (using an incremental exercise protocol of 60- s stage duration) and ~20km cycle time trial performance (Balmer et al., 2000a; Hawley and Noakes, 1992). In the study by Balmer et al. (2000a) they used the SRM crank system attached to the subjects own bicycle during the time trial. The PPO was well correlated to the average power output during the TT. That aside, the 'performance velocity' maybe still influenced by a number of morphological and biomechanical factors separate from those influencing performance power. Therefore, the relationship between PPO and indeed the LT and OBLA, and endurance performance in the field may be influenced by other factors not related to the athlete's physiological capacity that have been quantified in this experiment. Typically time trials especially in triathlon events are conducted on flat to very undulating courses. The body mass is known to be influential in the result of time trial events in the field (Swain, 1990). There is also evidence to suggest that during the cycle stage of an elite triathlon event the 'performance power' maybe dramatically shift in a 'stochastic' manner. Therefore, the characteristics of the event in combination with the subject's morphology may affect the overall result (or 'performance velocity'). These factors need to be examined at length before any conclusions can be made.

Hawley et al. (1997), suggested that endurance events are those that encompass a duration of greater than 20 min. With this in mind, endurance competitions may range from short duration (sprint triathlon, prologue cycling or 5000m running) or long duration (Marathon, Long distance or Ironman triathlon). The data from this experiment demonstrate that in trained cyclists the PPO and LT obtained from an incremental exercise test of 3 min stages most accurately reflect the average power output during a 90 min time trial. However, this relationship may not be evident over a duration of 20 min. This experiment suggests that the relationship between PPO and endurance performance may change depending upon the length of the endurance event being that is being examined. Therefore, a future examination of the metabolic responses between a 20 min and 90 min time trial is required. Furthermore, examining the metabolic responses to endurance exercise of short and long duration in subjects with different LT may provide an insight into the physiological factors associated with endurance performance in these events.

Peak power output, the lactate threshold, and time trial performance in cyclists

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ABSTRACT

BENTLEY, D. J., L. R. MCNAUGHTON, D. THOMPSON, V. E. VLECK, and A. M. BATTERHAM. Peak power output, the lactate threshold, and time trial performance in cyclists. *Med. Sci. Sports Exerc.*, Vol. 33, No. 12, 2001, pp. 2077–2081. **Purpose:** To determine the relationship between maximum workload (W_{peak}), the workload at the onset of blood lactate accumulation (W_{OBLA}), the lactate threshold (W_{LTlog}) and the D_{max} lactate threshold, and the average power output obtained during a 90-min ($W_{90\text{-}min}$) and a 20-min ($W_{20\text{-}min}$) time trial (TT) in a group of well-trained cyclists. **Methods:** Nine male cyclists ($\dot{V}O_{2max}$ 62.7 ± 0.8 mL·kg−1·min^{-1}) who were competing regularly in triathlon or cycle TT were recruited for the study. Each cyclist performed four tests on an SRM isokinetic cycle ergometer over a 2-wk period. The tests comprised 1) a continuous incremental ramp test for determination of maximal oxygen uptake ($\dot{V}O_{2max}$) (L·min^{-1} and mL·kg−1·min^{-1}); 2) a continuous incremental lactate test to measure W_{peak}, W_{OBLA}, W_{LTlog}, and the D_{max} lactate threshold; and 3) a 20-min TT and 4) a 90-min TT, both to determine the average power output (in watts). **Results:** The average power output during the 90-min TT ($W_{90\text{-}min}$) was significantly ($P < 0.01$) correlated with W_{peak} (r = 0.91), W_{LTlog} (r = 0.91), and the D_{max} lactate threshold (r = 0.77, $P < 0.05$). In contrast, $W_{20\text{-}min}$ was significantly ($P < 0.05$) related to $\dot{V}O_{2max}$ (L·min^{-1}) (r = 0.69) and W_{LTlog} (r = 0.67). The D_{max} lactate threshold was not significantly correlated to $W_{20\text{-}min}$ (r = 0.45). Furthermore, W_{OBLA} was not correlated to $W_{90\text{-}min}$ (r = 0.54) or $W_{20\text{-}min}$ (r = 0.23). In addition, $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) was not significantly related to $W_{90\text{-}min}$ (r = 0.11) or $W_{20\text{-}min}$ (r = 0.47). **Conclusion:** The results of this study demonstrate that in subelite cyclists the relationship between maximum power output and the power output at the lactate threshold, obtained during an incremental exercise test, may change depending on the length of the TT that is completed. **Key Words:** INCREMENTAL EXERCISE, MAXIMUM POWER OUTPUT, BLOOD LACTATE, CYCLING, ENDURANCE PERFORMANCE

The determination of physiological variables such as the anaerobic threshold (AT) and maximal oxygen uptake ($\dot{V}O_{2max}$) through incremental exercise testing, and the relevance of these variables to endurance performance, is a major requirement for coaches and athletes. Maximum oxygen uptake has been used as a valid indicator of superior performance in distance runners (12), but other studies have suggested that $\dot{V}O_{2max}$ is not a good predictor of 40-km cycle or 8-km running performance in triathletes (3,31). Furthermore, recent studies using elite cyclists as subjects have demonstrated that $\dot{V}O_{2max}$ is not a good indicator of cycling ability (10,23). However, the peak power output (W_{peak}), defined as the highest workload sustained for 2 to 3 min during progressive incremental exercise to exhaustion, has been shown to be highly related to time trial (TT) performance ranging from 21 to 40 km (3,6,17,30).

Other research groups have reported that the workload or oxygen consumption ($\dot{V}O_{2max}$) corresponding to set blood lactate concentrations or inflection points obtained during incremental exercise tests are better indicators of endurance performance than $\dot{V}O_{2max}$ (8,14,15). The workload eliciting a blood lactate concentration of 4 mmol·L^{-1} (also called onset of blood lactate accumulation (OBLA)), for example, has been used as an indicator of distance running ability (27). The D_{max} lactate threshold is determined by calculating the power output corresponding to the greatest perpendicular distance from a regression line of lactate to workload as well as a straight line formed by the first and last points of the regression line (7). In two recent investigations (7,8), it was established that the D_{max} lactate threshold and the OBLA were the two variables that were most related to the average power output achieved during 60 min of cycle exercise in female cyclists. Although these experiments report that either W_{peak} or submaximal workloads associated with certain blood lactate concentrations are indicative of successful endurance performance, the studies are limited by not reporting W_{peak}. In addition, the subjects participat-

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ng in the research were of mixed ability level ($\dot{V}O_{2max}$ ange, 35.5–57.9 mL·kg−1·min^{-1}) and would thus differ vith regard to W_{peak}.

TT in road cycling stage events are also held over dis-ances of 15 to 60 km as in an individual TT, and in the sport of triathlon, the cycle stage is completed over courses rang-ng from 20 to 180 km. Thus, in cycling and triathlon, the cycle stages range from less than 30 min to more than 240 nin. Typically, most investigations have examined cycling TT performance over distances and durations less than 60 nin (3,8,14). There are at present no data examining the elationship between variables obtained from an incremental exercise testing and cycle performance over short and onger duration (i.e., < 30 min or > 60 min) in well-trained specialist TT cyclists and triathletes.

In the present experiment, a group of well-trained cyclists completed a short (20 min) and long (90 min) TT as well as n incremental exercise testing procedure. These tests were mplemented to establish the relationship between the work-oad at a number of lactate inflection points previously used o assess trained cyclists (8,14) and the average power utput sustained during a long (90 min) and short (20 min) TT.

METHODS

Subjects

Nine male cyclists with the following characteristics mean ± standard deviation (SD)) volunteered to participate n the study: age, 32 ± 3 yr; body mass, 77.3 ± 4.8 kg; and eight, 185.5 ± 3.3 cm . At the time of recruitment, each ubject was competing in either TT or triathlon events that vere conducted over distances ranging from 16 to 90 km. The group included age group triathletes who had competed egularly in international (N = 4) and national (N = 3) level ompetitions or British Cycling Federation (BCF) category cyclists (N = 2). The procedures were explained to the ubjects both verbally and in writing. The subjects each rovided written informed consent. The institutional re-earch ethics committee approved the study.

Procedures

Each subject was required to complete four tests per-rmed on an SRM cycle ergometer (Schroberer Rad MeBtechnik, Weldorf, Germany) during a 2-wk period of ie competition phase of the training year (June to August). he cyclists were instructed to continue to train and not eviate from their planned schedules during the course of ie investigation. The four tests, each separated by at least 4 h, comprised 1) a continuous incremental ramp test, ndertaken first, with the following in random order: 2), a ntinuous incremental lactate test, 3) a 20-min TT, and 4) 90-min TT.

Incremental ramp test. The continuous incremental mp test was used to determine $\dot{V}O_{2max}$. The test com-enced following a 10- to 15-min warm-up at a self-se-cted intensity not exceeding approximately 50% of $\dot{V}O_{2max}$ The initial test workload was set at 150 W for 60 s, after which power output was increased by 30 W·min^{-1} until exhaustion, which was always within 12 min. During the test, expired gases were continuously monitored breath by breath through a mass spectrometer (EX670, Morgan Medical Ltd., Gilingham, United Kingdom) for determination of $\dot{V}O_{2max}$ and respiratory exchange ratio (RER). The system was calibrated with known volumes (3 L Hans Rudolph Syringe, Hans Rudolph, Kansas City, MO) and concentrations of gas prior (O_2, CO_2, N_2, Ar) to each test. Heart rate (HR) was recorded every 5 s during the test using a portable HR monitor (Polar Vantage, Finland). Maximal exertion was deemed to have occurred if $\dot{V}O_{2max}$ failed to rise (< 200 mL O_2) with a subsequent increase in workload, an RER > 1.2, and HR_{max} within 5 b·min^{-1} of age-predicted HR (220 − age). $\dot{V}O_{2max}$ was determined as the highest consecutive breath-by-breath $\dot{V}O_{2max}$ point obtained during any 60-s period of the test.

Incremental lactate test. A continuous incremental lactate test was used to determine the power output (in watts) at the lactate threshold (LT) (5), the OBLA (27), the D_{max} lactate threshold (8), and W_{peak} (17). The test commenced without warm-up at a workload representing 50% $\dot{V}O_{2max}$ for 3 min. After the initial 3-min stage, the required workload increased by approximately 5% of $\dot{V}O_{2max}$ every 3 min until voluntary exhaustion occurred (13). Capillary blood samples were obtained from the left ear lobe in the last 30 s of each workload as well as at the end of the test and were analyzed for whole blood lactate using a portable lactate analyzer (LT 1710 Lactate Pro, KDK Corporation, Shiga, Japan). The reliability and validity of this device has been previously determined (26).

Blood lactate concentration (in mmol·L^{-1}) was plotted against power output (in watts) during the incremental lactate test. A third-order polynomial curve was then constructed from the data points. The LT (W_{LTlog}) was determined as the power output (in watts) at which lactate increases exponentially when the log ([La^-]) is plotted against the log (in watts) (5). The OBLA (W_{OBLA}) was determined as the power output eliciting a lactate concentration of 4 mmol·L^{-1} (27). The D_{max} lactate threshold was calculated as the point (in watts) on the polynomial curve forming the greatest perpendicular distance to a straight line formed by the first and last data points (8). The W_{LTlog}, W_{OBLA}, and D_{max} lactate threshold were calculated by interpolation using a custom written workbook (Microsoft Excel for Windows 7.0, Microsoft, Redmond, WA).

Cycle TT. The cycle TT were performed over 20 min and 90 min on the SRM cycle ergometer at a freely selected pedaling cadence. Another study has reported high reproducibility of cycle TT of short and long duration (18). The subjects refrained from any high-intensity/long-duration training for 48 h before each test. Each subject was instructed to prepare for each trial as they would for a normal competition and were instructed to consume high-carbohydrate (CHO) foods and regular quantities of fluid in the 48 h before each trial. Written guidelines were administered to each subject with regard to correct nutritional strategies.

Thirty minutes before the 90-min TT, 500 mL of fluid (Lucozade Sport, Smith Kline Beecham, Brentford, United Kingdom) containing 32 g of CHO was ingested. During the trial, a further 250 mL was consumed every 15 min to control for possible dehydration and substrate depletion (2). Body mass (in kilograms) was obtained with subjects wearing only Lycra cycling shorts using a balance beam (Weylux, England) before and after the trials to determine the extent of fluid loss (range, 0.3–1.3 kg) attributable to sweating. During both TT, electrical fans were positioned around the cyclist to allow circulation of air. Each of the trials were performed at the same time of day to control for any diurnal variation in performance and were supervised by the same researcher.

Before each test, 15 min of warm-up was allowed at a self-selected intensity not exceeding 50% $\dot{V}O_{2max}$. After a 30-s period where the subject was instructed to increase the power output to approximately 70% of W_{peak}, the trial commenced and the subject was free to vary the power output and pedaling frequency at their own discretion. Performance was evaluated by determining the average power output that each subject could maintain for the test duration.

Each incremental test and TT was performed on an SRM isokinetic cycle ergometer calibrated using the manufacturer's recommendations. The SRM cycle ergometer allows adjustments to be made so that the dimensions of the cyclist's own bicycle set-up are obtained. Clipless pedals were also attached so that the cyclist could wear their own shoes.

The SRM crank system has also been confirmed as valid and reliable in determining maximal and submaximal power output data (4). Briefly, the SRM cycle ergometer is designed so that power output is calculated by the average torque of one crank revolution multiplied by the angular velocity of one crank revolution via a power control unit. The power control unit is integrated to the crank system of the ergometer. The power output is sampled at 1-s intervals and transferred to the SRM software downloaded to a personal computer.

Statistical Analyses

Mean and SD were calculated for $\dot{V}O_{2max}$ (in $L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$) obtained during the ramp test. Descriptive statistics were also calculated for W_{peak} (in watts), W_{LTlog}, W_{OBLA}, and the D_{max} lactate threshold (in watts). In addition, average power output (in watts) during the 90-min ($W_{90\text{-}min}$) and 20-min ($W_{20\text{-}min}$) TT were also obtained. The relationship between $W_{90\text{-}min}$ and $W_{20\text{-}min}$ and each variable during the incremental exercise tests were determined using Pearson product correlations and linear regression analysis. A paired sample *t*-test was used to compare the $W_{90\text{-}min}$ and $W_{20\text{-}min}$. Statistical significance was set at $P < 0.05$.

TABLE 1. Mean ± SD for variables obtained during the incremental lactate test.

Variable	Mean ± SD
W_{peak} (W)	358.3 ± 15.6
W_{OBLA} (W)	285.7 ± 32.3
D_{max} (W)	281.6 ± 24.2
W_{LTlog} (W)	247.6 ± 37.1

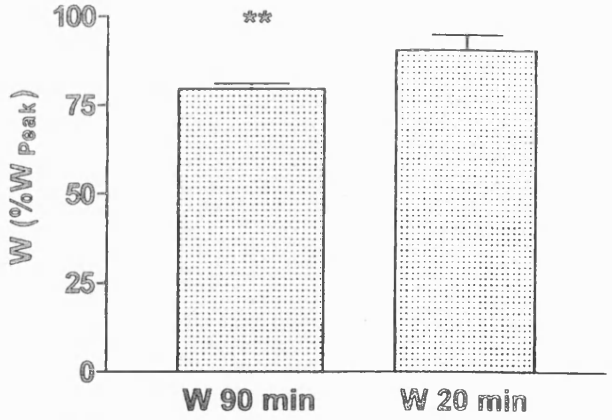


FIGURE 1—Mean ± SD power output (in watts) as a percentage (%) of maximum power output (W_{peak}) during the 90-min ($W_{90\text{-}min}$) and 20-min ($W_{20\text{-}min}$) cycle TT. **Significantly different from $W_{20\text{-}min}$ $P < 0.01$.

RESULTS

The mean (± SD) $\dot{V}O_{2max}$ of the cyclists were 4.85 ± 0.3 $L \cdot min^{-1}$ and 62.7 ± 4.8 $mL \cdot kg^{-1} - 1 \cdot min^{-1}$, respectively. The physiological variables obtained in the incremental lactate tests are shown in Table 1. The average power output (in watts) in the 20-min TT and the 90-min TT was 323.7 ± 17.2 and 284.3 ± 8.6, respectively. Figure 1 demonstrates the average power output (in watts) during the 90-min ($W_{90\text{-}min}$) and 20-min ($W_{20\text{-}min}$) TT as a percentage of W_{peak}. The $W_{20\text{-}min}$ and $W_{90\text{-}min}$ during the TT was significantly ($P < 0.01$) different. Furthermore, $W_{20\text{-}min}$ was not correlated ($r = 0.66$, $P = 0.54$) to $W_{90\text{-}min}$. Correlation coefficients between each physiological variable obtained from the incremental exercise testing, $W_{90\text{-}min}$ and $W_{20\text{-}min}$, are shown in Table 2. Figure 2 graphically demonstrates the relationship between W_{peak} and $W_{90\text{-}min}$.

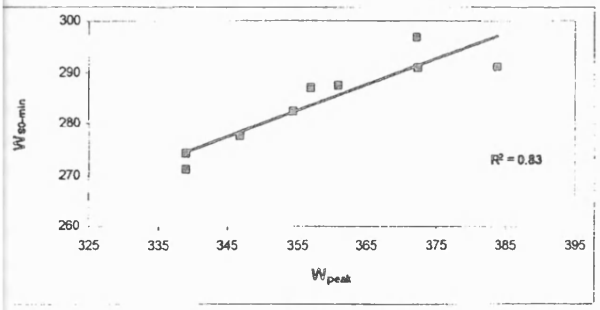
DISCUSSION

Previous studies have shown the W_{peak} obtained during an incremental cycle test to exhaustion is a valid and reliable indicator of endurance cycle performance (3,17). However, this study was conducted to examine whether this variable correlated with cycle TT performance over durations of 20 min or 90 min. The cyclists in this study were not elite and

TABLE 2. Correlation coefficients between each variable obtained from the ramp as well as incremental lactate tests and average power output during the 90-min ($W_{90\text{-}min}$) and 20-min ($W_{20\text{-}min}$) TT.

Variable	$W_{20\text{-}min}$	$W_{90\text{-}min}$
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	0.69*	0.38
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	0.47	0.11
W_{peak} (W)	0.54	0.91**
W_{LTlog} (W)	0.67*	0.91**
W_{OBLA} (W)	0.23	0.54
D_{max} (W)	0.45	0.77*

$\dot{V}O_{2max}$, maximal oxygen uptake obtained in the ramp test; W_{peak}, maximum power output obtained in the lactate test; W_{LTlog}, power output when blood lactate increases when log ([La^-]) is plotted against log (W); W_{OBLA}, power output at a blood lactate concentration of 4 $mmol \cdot L^{-1}$; D_{max}, the lactate threshold as determined by the D_{max} method.
* $P < 0.05$; ** $P < 0.01$.



IGURE 2—The relationship between maximum power output W_{peak}) and mean power output during the 90-min TT ($W_{90\text{-}min}$).

ossessed an average $\dot{V}O_{2max}$ (in $L \cdot min^{-1}$) of 4.85, which is ›wer than data presented concerning professional cyclists 10,23,25). The results of the study demonstrate that 90-min T performance was highly related to W_{peak}, W_{LTlog}, and ıe D_{max} lactate threshold. In contrast, 20-min TT perfor- ıance was only moderately correlated to $\dot{V}O_{2max}$ (in $\cdot min^{-1}$) and W_{LTlog}. Interestingly, 20-min TT performance as not related to 90-min TT performance.

In the present study, W_{peak} was highly related to the verage power output in a 90-min but not a 20-min TT. ıdeed, 83% of the variance in $W_{90\text{-}min}$ was explained by W_{peak}, but only 29% for $W_{20\text{-}min}$. Another experiment has ported the maximum workload (or the "peak power out- ıt") obtained during an incremental exercise test is related the average power output during a cycle TT over a stance of 16.1 km (r = 0.99) (3). A similar negative lationship has also been reported between peak power ıtput and the time taken (in minutes) to complete 20 km (r −0.91) (17) or 40 km (r = −0.87) (6). In two other aining studies, high correlation coefficients have been ported between the maximum workload and the time (in inutes) (r = −0.91) or average speed (in $km \cdot h^{-1}$) (r = 83) during a 40-km cycle TT (29,30). It has been recently ported that the relationship between maximum workload d TT performance is reduced when the time taken to mplete a set distance is utilized (3). It is also likely that the orter duration incremental protocol used in the studies by eston et al. (30) and Westgarth-Taylor et al. (29) may ve resulted in a higher maximum power output than that tained in the current study. Unpublished data from this oratory demonstrates that the maximum workload during shorter ramp test to exhaustion is not related to cycle TT rformance. Thus, the incremental exercise protocol used determine W_{peak} together with performance measure (i.e., erage speed, power output, or elapsed time) may influ- ce the relationship between these sets of variables. Further rk is needed to examine the reliability and validity of peak obtained during different incremental exercise proto- ls and the relationship to endurance performance differing mode and duration.

The average power output sustained by the cyclists in this dy during the 90-min TT was not related to the average wer output during the 20-min TT. As exercise intensity reases above the LT, the utilization of glycogen for energy metabolism is elevated (28). The average power output during the 20-min TT approximated 90% of W_{peak}, which is higher than the workload at the W_{LTlog} and the average power output during the 90-min TT. Therefore, it is likely that accumulation of lactic acid was much greater during the 20-min TT than in the 90-min TT. Thus, power output decrement during the shorter duration TT may have been influenced to a greater extent by metabolic acidosis rather than substrate depletion. In contrast to shorter duration endurance exercise, previous studies have also shown that during endurance exercise lasting more than 60 min the utilization of free fatty acids (FFA) and triglycerides increases (21,22). It is also well known that endurance training enhances the capacity of skeletal muscle to utilize FFA, thus delaying the reduction in work output as a consequence of glycogen depletion (19). From the data presented in these studies, it is possible that substrate depletion may have been more influential during the 90-min TT as opposed to a disruption of the contraction process by metabolic acidosis (1) during the 20-min TT. This aside, other studies have quantified the exercise intensity during cycle TT in using heart rates coupled with incremental exercise test results (25). These studies suggest that elite cyclists spend a greater portion of the exercise time above the LT in TT lasting 60-min, which would result in substantial accumulation of blood lactate. The findings of the present study suggest that heightened adaptation of processes effecting lactate metabolism such as acid-base balance or FFA metabolism may be more influential during the 20-min or 90-min TT, respectively. It is also very likely that the metabolic response to a 20-min and 90-min TT will be affected by the ability level of the cyclists being tested.

It is common for the workload associated with set lactate values (i.e., the OBLA), inflection points, or mathematical models such as the D_{max} lactate threshold to be used to assess endurance athletes (7,8). The results demonstrate that W_{LTlog} was related to both 20-min and 90-min TT performances. However, only 45% of the variation in $W_{20\text{-}min}$ was explained by W_{Ltlog}, in contrast to 83% for $W_{90\text{-}min}$. The D_{max} lactate threshold was also highly related to 90-min (r^2 = 0.59) but not 20-min TT performance (r^2 = 0.20). However, the W_{OBLA} was not related to either 20-min or 90-min TT performance.

Theoretically, athletes with an elevated power output at the LT may exercise at a higher work rate without accumulation of blood lactate compared with those with a lower power output at the LT. The LT is also known to be related to muscle oxidative capacity (20), and this is thought to be one factor that positively influences FFA metabolism during prolonged submaximal exercise (11,15). Therefore, it is likely that these characteristics associated with the W_{LTlog} partly explained the high correlation of this variable to $W_{90\text{-}min}$. However, the fact that only 45% of the variation in $W_{20\text{-}min}$ was explained by W_{LTlog} seems to indicate that other factors aside from the ability to delay lactate accumulation during incremental exercise may reflect short TT performance.

In contrast to other investigations (8,27), the present results show that W_{OBLA} was not related to either the average power output during the 20-min or 90-min TT. One difficulty that has been reported in using the workload at set blood lactate concentrations is the extreme variability in lactate diffusion from muscle into the blood (24). Other factors associated with lactate transportation and elimination from the exercising muscle may influence the blood lactate concentration during incremental exercise (9). Therefore, it is possible the W_{OBLA} may not be a reflection of the muscle metabolic stress that occurred at the workload eliciting the set lactate concentrations.

Hawley et al. (16) suggested that endurance events are those that encompass a duration of greater than 20 min. With this in mind, endurance competitions may range from short duration (sprint triathlon, prologue cycling, or 5000-m running) to long duration (marathon, long distance, or Ironman triathlon). The data from this study demonstrate that in trained cyclists W_{peak} is correlated to the average power output during a 90-min TT. However, this relationship may not be evident over a duration of 20 min. This study suggests that the relationship between W_{peak} and endurance performance may change depending on the length of the endurance event being that is being examined.

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CHAPTER SEVEN

EXPERIMENT FOUR

Physiological responses to endurance exercise in cyclists with high or low lactate threshold

CHAPTER SEVEN – EXPERIMENT FOUR

7.1 Introduction

Energy (ATP) resynthesis during endurance exercise can occur via utilisation of either carbohydrate (CHO) or fat. Both the duration and intensity of exercise represent major influences on substrate utilisation, metabolic end products and possible fatigue manifestation (Romijn et al., 1993). Depending upon the exercise intensity and duration, trained athletes are thought to be able to withstand fatigue during prolonged exercise by more efficient energy provision and increased metabolic waste elimination such as muscle lactate dissipation (Noakes, 2000).

In circumstances when the exercise intensity dramatically increases relative to maximal oxygen uptake ($\dot{V}O_2max$) the energy requirement from blood glucose and muscle glycogen sources also increases (Romijn et al., 1993). As glycogen stores are limited, muscle contraction and performance may be disrupted during exercise at an elevated intensity because of a reduction in the supply of substrates necessary to maintain the required work output (Coyle et al., 1986). A number of endurance events such as triathlon and distance running are completed at high intensity (> 80% $\dot{V}O_2max$) but over duration of > 60 min. Although, CHO utilisation may form a major component of energy metabolism in these circumstances (O'Brien et al., 1993), it has been shown in untrained subjects that utilisation of fat increases during exercise > 60min in duration (Kiens et al.,

1993). However, one possible influence on the metabolic response to endurance exercise of short <30 min or long > 60 min duration is the LT (Coyle et al., 1988).

The results of study three demonstrated that in well-trained cyclists, the power output corresponding to the lactate threshold (LT), together with power output expressed as a percentage of $PPO_{3\ min}$, were highly correlated ($r=0.85$ to 0.91; $p<0.01$) to the average power output that could be sustained during a 90 min cycling time trial. This relationship was not as evident for a shorter, 20 min time trial. This data therefore suggests that athletes with an elevated LT (but similar $\dot{V}O_2max$) have a better capacity to perform prolonged exercise (> 60 min) at a higher work output than subjects with a lower LT. However, whilst it is widely acknowledged that an elevated LT is indicative of successful endurance performance *overall* (Coyle, 1995; Coyle, 1999; Bassett and Howley, 2000), there is limited data examining the metabolic responses during endurance exercise of athletes with a similarly elevated aerobic capacity but with different LT over a duration typical of cycling time trial events i.e. ~ 30 min or > 60 min (Coyle et al., 1988; Coggan et al., 1992). Especially when the exercise trial is > 60 min duration.

Aim

To determine whether trained cyclists with a high LT (W or % $PPO_{3\ min}$) exhibit contrasting metabolic responses (as measured by whole body gas exchange and blood metabolite measurements) during a 20 min and 90 min submaximal exercise bout to subjects with a low LT regardless of a similar $\dot{V}O_2max$.

7.2 Methodology

7.2.1 Subjects

Fifteen male subjects were recruited for the investigation. All of the subjects were competing in road cycling or triathlon events. Criteria for inclusion in the experiment was a $\dot{V}O_2$max and $PPO_{3\ min}$ value of ~ 60 $ml \cdot kg^{-1} \cdot min^{-1}$ and 4.5 $W \cdot kg^{-1}$. This criteria enabled recruitment of a subject population that was 'well-trained' but not 'elite' (Jeukendrup et al., 2000) and homogeneous in terms of maximal levels obtained during an incremental exercise test.

7.2.2 Procedures

Each subject performed four exercise tests over a 14 day period on a cycle ergometer [Schroberer Rad MeBtechnik (SRM), Weldorf, Germany). The testing involved two incremental exercise tests and two set workload exercise trials (See 'General Materials and Methods'). The first incremental exercise test involved a 'ramp' test ($EXT_{60\text{-}s}$) for determination of $\dot{V}O_2$max ($ml \cdot min^{-1}$) and HR_{max} ($b \cdot min^{-1}$). This protocol was thought to elicit the highest possible $\dot{V}O_2$ value for purposes of subject characterisation (See 'Results – experiment Two'). The second test involved a continuous 'lactate' test ($EXT_{3\ min}$) for determination of the $PPO_{3\ min}$ and the LT (W and $\%PPO_{3\ min}$). The LT was calculated using the procedures of Beaver et al. (1985) (See 'General Materials and Methods'). The third and fourth tests involved set workload rides of duration 20 min and 90 min at 85 and 75% $PPO_{3\ min}$ respectively. The length and intensity of the trials was used because in experiment three it was demonstrated that in well trained cyclists the

average power output that could be sustained during TT of this duration represented ~80 and 90% $PPO_{3\ min}$. A workload of <5% of this figure was selected because it ensured that all the subjects would be able to complete the trial. Fifteen min prior to the trial the subjects consumed 250 ml of an 8% CHO solution. During the 90 min trial a further 250 ml of 8% CHO drink was consumed every 15 min (Jeukendrup and Jentjens, 2000). No further CHO drink was consumed in the 20 min trial (similarly to the procedures of experiment three). The LT (W and % $PPO_{3\ min}$) were selected as the physiological variables to distinguish the subjects because in experiment three these variables were shown to be highly correlated to 90 min TT performance, but not 20 min cycle TT performance. The $EXT_{60\text{-}s}$ was always completed first because it was required to determine the workloads completed in $EXT_{3\ min}$. The $EXT_{3\ min}$ was completed second and then the remaining submaximal tests were completed last in a randomised order.

Table 7.2.1. Outline of the 90 min set workload exercise trial

↑ = Blood sample, expired gas

BM = body mass measurement

Expired gas and HR measured in the 2 min period around blood sample i.e. 60-s before and 60-s after sample with the exception of the first 2 min and final 2 min.

250 ml of CHO drink consumed 15 min prior to the trial and every 15 min of exercise i.e. 15, 30,45, 60, 75 min

WARM UP		MAIN EXERCISE					
10 min at 50% of $PPO_{3\ min}$		90 min at 75% of $PPO_{3\ min}$					
-15 min	-10 min	0 min	18 min	36 min	54 min	72 min	90 min
		↑	↑	↑	↑	↑	↑
BM + CHO							

Table 7.2.2. Outline of the 20 min set workload exercise trial

↑ = Blood sample, expired gas

BM = body mass measurement

Expired gas, RPE and HR measured in the 2 min period around blood sample i.e. 60-s before and 60-s after sample with the exception of the first 2 min and final 2 min.

250 ml of CHO drink consumed 15 min prior to the trial. None consumed during the trial.

WARM UP		MAIN EXERCISE					
10 min at 50% of $PPO_{3\ min}$		20 min at 85% of $PPO_{3\ min}$					
-15 min	-10 min	0 min	4 min	8 min	12 min	16 min	20 min
		↑	↑	↑	↑	↑	↑
BM + CHO							

7.2.3 Physiological Measurements

During the 20 min and 90 min exercise trial, the subjects breathed into a mask connected to a breath by breath gas analysis system (Cosmed, K4, B2, Italy). During the 90 min trial expired gases were collected in the first and final 2 min of exercise. Also, 2 min breath by breath samples were obtained at 18, 36, 54, 72 min of the trial. During the 20 min trial expired gases were collected continuously and 2 min gas samples were averaged at the same relative (%) (to the total duration of the trial) time points as in the 90 min trial. These time points correspond to 20, 40, 60, 80 and 100% of each trial. Each 2 min sample was averaged for determination of oxygen consumption ($\dot{V}O_2$) ($ml \cdot kg^{-1} \cdot min^{-1}$), carbon dioxide production ($\dot{V}CO_2$) ($ml \cdot min^{-1}$) and pulmonary ventilation ($\dot{V}E$) ($ml \cdot min^{-1}$). The $\dot{V}O_2$ was also expressed as a % of $\dot{V}O_2max$ obtained in the $EXT_{60\text{-}s}$. $\dot{V}O_2$ and $\dot{V}CO_2$ were subsequently used to calculate from respiratory exchange ratio (RER). In addition, the rate of CHO and fat oxidation ($g \cdot min^{-1}$) were determined using the $\dot{V}O_2$ and $\dot{V}CO_2$ (expressed in $L \cdot min^{-1}$) obtained in the 90 min exercise trial assuming a non-protein RER value (Frayn, 1983). The % of energy derived from CHO and fat during the 90 min trial was calculated from the tables presented by Peronnet and Massicotte (1991). Substrate oxidation rate was not determined in the 20 min exercise trial because the RER value for the greater part of the trial was > 1.0. Heart rate ($b \cdot min^{-1}$) was sampled continuously using a portable HR monitor (Polar, Finland) integrated with the SRM software. The HR ($b \cdot min^{-1}$) was averaged for 2 min period corresponding to when the expired gas samples were obtained. The averaged HR values were expressed as a percentage of HR_{max} obtained from the $EXT_{60\text{-}s}$. The power output (W) was also continually maintained at the

desired intensity using the SRM software. In contrast, the pedalling frequency (rpm) was self-selected. The power output (W) and pedalling frequency was averaged for the duration of the trial as well as at each time point around the gas sampling points. The power output was expressed in absolute terms (W) as well as relative to $PPO_{3\ min}$. An outline of the 90 min and 20 min exercise trials are shown in Table 7.2.1 and 7.2.2.

7.2.4 Venous blood collection and analysis

During the set workload exercise trials venous blood (5 ml) was collected via a 19 gauge butterfly needle with a three way stopcock inserted into the anticubital vein prior to the test (See 'General Materials and Methods'). The subject remained seated on the cycle ergometer and a baseline blood sample was obtained. There after, blood samples were collected at 18, 36, 54, 72 min and in the final 2 min during the 90 min trial. During the 20 min trial blood samples were obtained every 4 min. These time points correspond to 20, 40, 60, 80 and 100% of the trial and corresponded to when the expired gas concentrations were obtained. A portion of each sample was analysed immediately for whole blood lactate concentration (mM) using a laboratory based metabolite analyser (YSI). Whole blood pH and HCO_3- (mM) was also analysed using an automatic blood gas analyser (AVL 993, AVL Medical, Switzerland).

7.2.5 Data treatment and statistical analysis

Each subject was ranked in the regards to the LT (% $PPO_{3\ min}$) obtained during the $EXT_{3\ min}$. Twelve of the 15 subjects were then placed into two equal groups (n=6). The six subjects with the highest LT were designated as group 'high' and the six subjects with the

lowest LT were designated as 'low'. The remaining three subjects were eliminated from the data analysis. Similar procedures and subject numbers have been used before to establish two groups with highly variable anaerobic thresholds (% $\dot{V}O_2$max) (Coyle et al., 1988; Loftin and Warren, 1994). The maximal physiological variables obtained from the $EXT_{60\text{-}s}$ and $EXT_{3\ min}$ plus the LT obtained from the $EXT_{3\ min}$ for each group were compared using a series of single factor (subject group) ANOVA. The average power output in the 20 min and 90 min trials relative to the work rate at the LT (% and W) in the 'high' and 'low' groups was examined using a two factor (subject group by exercise trial) ANOVA. The average physiological responses in each trial in subjects belonging to the high and low groups averaged over the entire trial were compared using a series of two factor (subject group by exercise trial) ANOVA. The same variables obtained from each exercise trial at the different sampling points were compared using additional two factor (subject group by exercise trial) ANOVA with repeated measures. The relationship between CHO and fat oxidation, total energy expenditure during each exercise trial and the LT was determined using Pearson Product moment correlation. Additional correlation co-efficient were calculated between whole blood lactate concentration post exercise and the LT. Furthermore, correlation co-efficient were determined between $PPO_{3\ min}$ (W) and the power output (W and $\%PPO_{3\ min}$) corresponding to the LT. Significance was accepted at $p<0.05$.

7.3 Results

7.3.1 Physiological characteristics of the 'high' and 'low' groups

The mean (±SD) physiological and anthropometrical characteristics of the subjects in the 'high' and 'low' groups is shown in Table 7.3.1. There were no significant differences in the age, maximal physiological variables or the anthropometrical characteristics of the subjects in the two groups.

Table 7.3.1. Mean (±SD) physiological and anthropometrical characteristics of the subjects (n=12) in the high and low lactate threshold groups.

	High (n=6)	Low (n=6)
Age (yr)	27.0 ± 4.9	28.0 ± 6.9
Body Mass (kg)	72.6 ± 6.2	73.5 ± 3.7
Height (cm)	179.9 ± 4.7	182.1 ± 4.7
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	61.6 ± 1.3	65.8 ± 4.8
$PPO_{3\ min}$ (W)	308.7 ± 32.3	337.5 ± 26.7
HRmax ($b \cdot min^{-1}$)	189.2 ± 10.9	186.5 ± 7.4

No significant differences

7.3.2 *Comparison of the LT and the average power output in the 20 min and 90 min trials.*

The power output produced by the cyclists was significantly ($p<0.01$) higher in the 20 min than in the 90 min trials when expressed in absolute terms (W) or relative (%) to $PPO_{3\ min}$. (Table 7.3.2 and 7.3.3). However, this difference was not significant. At the same time, the power output expressed relative (%) to $PPO_{3\ min}$ was not significantly different in each group in the 20 min or 90 min trials. (Table 7.3.3). There was significant

($p<0.01$) correlation ($r=0.77$) between the $PPO_{3\ min}$ and LT expressed in absolute (W) terms. There was a significant correlation between $PPO_{3\ min}$ and the LT (W) ($r=0.77$; $p<0.01$). However, the $PPO_{3\ min}$ (W) and LT ($\%PPO_{3\ min}$) were not significantly correlated ($r=-0.10$).

In each case (high or low group) the LT (W) was significantly ($p<0.01$) higher than the average power output in the 20 min trial, but not the 90 min trial (Table 7.2.2). Also, the average power output in the 20 min trial was significantly ($p<0.01$) higher than the 90 min trial.

The LT ($\%PPO_{3\ min}$) was significantly ($p<0.01$) greater in subjects belonging to the high group as compared to the low group (Table 7.2.3). There was also a significant ($p<0.01$) difference between the LT and the average power output ($\%PPO_{3\ min}$) in the 20 min trial in both groups of subjects. However, the LT expressed relative to $PPO_{3\ min}$ was not significantly different to the power output in the 90 min trial ($\%PPO_{3\ min}$) in subjects in the high group. In contrast, the LT was significantly ($p<0.01$) lower compared with the average power output in the 90 min trial in subjects with a low LT.

Table 7.2.2. Mean (±SD) power output (W) during the 20 min and 90 min trial as well as corresponding to the LT of the subjects in the high and low lactate threshold groups.

	High	Low
LT (W)	$227.8 \pm 33.3^{a}_{x}$	$219.5 \pm 20.0^{a}_{x}$
Power output (W) (20 min trial)	$260.8 \pm 28.9^{a}_{y}$	$282.4 \pm 22.4^{a}_{y}$
Power output (W) (90 min trial)	$230.3 \pm 23.9^{a}_{x}$	$252.2 \pm 19.7^{a}_{x}$

Different suprascripts^{a,b} indicate a significant ($p<0.05$) difference between high and low groups. Different subscripts$_{x,y,z}$ indicate a significant difference ($p<0.05$) from LT (W).

Table 7.2.3. Mean (±SD) power output (%$PPO_{3\ min}$) during the 20 min and 90 min trial as well as corresponding to the LT of the subjects in the high and low lactate threshold groups.

	High	Low
LT (%$PPO_{3\ min}$)	$74.6 \pm 0.1^{a}_{x}$	$65.0 \pm 1.7^{b}_{x}$
Power output (%$PPO_{3\ min}$) (20 min trial)	$83.7 \pm 0.3^{a}_{y}$	$83.7 \pm 0.7^{a}_{y}$
Power output (%$PPO_{3\ min}$) (90 min trial)	$73.6 \pm 3.2^{a}_{x}$	$74.7 \pm 0.2^{a}_{z}$

Different suprascripts^{a,b} indicate a significant ($p<0.05$) difference between high and low groups. Different subscripts$_{x,y,z}$ indicate a significant difference ($p<0.05$) from LT (%$PPO_{3\ min}$).

7.3.3 Overall physiological responses during the exercise trials.

One subject out of each of the high and low groups failed to complete the 90 min trial. In both cases fatigue occurred at 53 min.

The average $\dot{V}O_2$, expressed in absolute ($ml \cdot kg^{-1} \cdot min^{-1}$) terms and relative (%) to $\dot{V}O_2max$ was significantly ($p<0.01$) higher in the 20 min as compared to the 90 min trial (Table 7.3.4). However, there were no significant differences in these variables between the subjects in the high and low groups when measured during the two trials (Table 7.3.4). This trend was also similar for VE, $\dot{V}CO_2$ and the RER. Thus, significantly higher values were found for VE ($L \cdot min^{-1}$), ($p<0.01$), $\dot{V}CO_2$ ($ml \cdot min^{-1}$) ($p<0.01$) and RER ($p<0.05$) in the 20 min as compared with the 90 min exercise trial. However, there were no significant differences in these variables in each exercise trial when the subjects in the 'high' or 'low' group were compared.

The average HR expressed in absolute terms ($b \cdot min^{-1}$) or relative to HRmax was not significantly different in the 20 min and 90 min trials or when the high and low groups were compared (Table 7.3.4).

The average pedalling frequency (rpm) was not significantly different in the 20 min and 90 min trials. There were also no significant differences in the average pedalling frequency in the subjects belonging to the low and high groups in the 20 min or 90 min trials (Table 7.3.4).

Table 7.3.4. The mean (±SD) physiological variables calculated over the entire exercise period in the 20 min and 90 min trials in the cyclists with high or low lactate threshold.

Variable	Group					
	Low		High		Total	
	20 min	90 min	20 min	90 min	20 min	90 min
$\dot{V}O_2$ ($ml \cdot kg^{-1} min^{-1}$)	52.6 ± 4.4	45.9 ± 2.0**	49.1 ± 6.0	42.1 ± 2.2**	51.0 ± 5.2	43.8 ± 2.9**
$\dot{V}O_2$ (% $\dot{V}O_2$max)	80.2 ± 8.1	69.4 ± 4.3**	79.8 ± 11.3	68.2 ± 3.3**	80.0 ± 8.2	68.7 ± 3.6**
$\dot{V}CO_2$ ($ml \cdot min^{-1}$)	3939.7 ± 458.3	2832.2±345.9**	3768.1 ± 424.6	3042.5±371.6**	3861.7 ± 430.3	2949.1±355.2**
RER	1.00 ± 0.07	0.90 ± 0.01*	0.99 ± 0.12	0.94 ± 0.05*	1.00 ± 0.09	0.92 ± 0.04*
VE ($ml \cdot min^{-1}$)	104.5 ± 14.5	78.1 ± 11.3**	91.3 ± 11.3	74.1 ± 10.9**	98.5 ± 14.3	76.1 ± 10.7**
Heart rate (%HRmax)	89.4 ± 5.4	88.0 ± 5.4	87.8 ± 1.6	86.4 ± 2.9	88.7 ± 4.0	87.2 ± 4.2
Heart rate ($b \cdot min^{-1}$)	166.6 ± 8.9	163.8 ± 8.3	165.6 ± 9.4	163.3 ± 6.8	166.2 ± 8.7	163.6 ± 7.3
Pedalling frequency (rpm)	91.3 ± 6.9	90.7 ± 5.8	93.1 ± 4.3	91.5 ± 5.9	92.1 ± 5.7	91.1 ± 5.6

Significantly different from 20 min (** $p<0.01$; * $p<0.05$) in each group ('low', 'high' or 'total')

7.3.4 Longitudinal physiological responses during the exercise trials in the 'high' and 'low' groups.

With the exception of the first expired gas collection point the average $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) was significantly higher ($p<0.05$) at all periods during the 20 min trial as compared with the 90 min trial. This was also evident when the $\dot{V}O_2$ was expressed relative to $\dot{V}O_2max$. The average $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$ and $\%\dot{V}O_2max$) was also significantly ($p<0.01$) higher at all sampling points throughout each exercise trial as compared with the first sampling point. In both the 20 min and 90 min trials the $\dot{V}O_2$ increased then reached a plateau from ~ 20% of the trial. However, there were no other significant differences when each sampling point was compared to the first sampling point in each exercise trial. Although the $\dot{V}O_2$ was generally higher in the subjects belonging to the low group, there were no significant differences between the high and low group in either the 20 min or 90 min trial (Figure 7.3.1 to 7.3.4).

Carbon dioxide production ($\dot{V}CO_2$) ($ml \cdot min^{-1}$) was significantly ($p<0.01$) higher in the 20 min as compared with the 90 min trial at all time points with the exception of the first sampling point. The $\dot{V}CO_2$ was also significantly ($p<0.01$) higher at 20% as compared with 0% of the total duration of each trial, whether this was in the 20 min or 90 min trial. From this point on, $\dot{V}CO_2$ remained significantly ($p<0.01$) elevated above the value measured at the first sampling point start of the trial. The $\dot{V}CO_2$ was highest in both trials

each in the low LT group as compared with the high group and approached statistical significance ($p<0.1$) (Figure 7.3.5 and 7.3.6).

Figure 7.3.1. Mean (±SD) oxygen uptake ($\dot{V}O_2$) (%$\dot{V}O_2$max) for the duration of the 20-min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

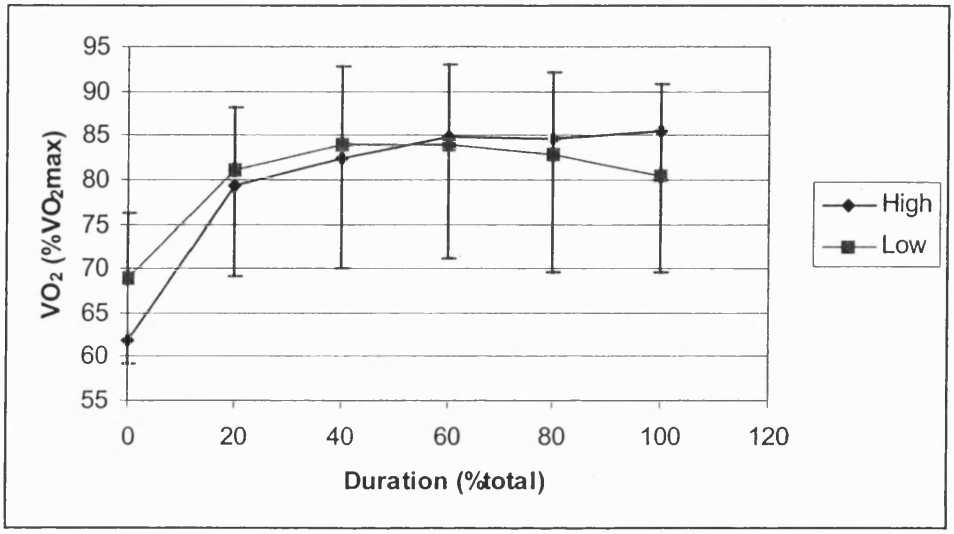


Figure 7.3.2. Mean (±SD) oxygen uptake ($\dot{V}O_2$) (%$\dot{V}O_2$max) for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

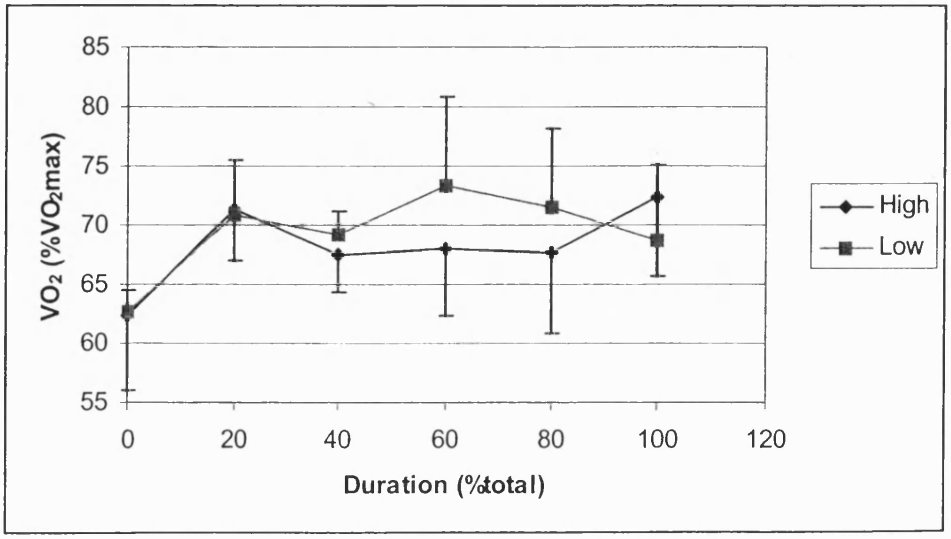


Figure 7.3.3. Mean (±SD) oxygen uptake ($\dot{V}O_2$) (ml·kg^{-1}·min^{-1}) for the duration of the 20 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

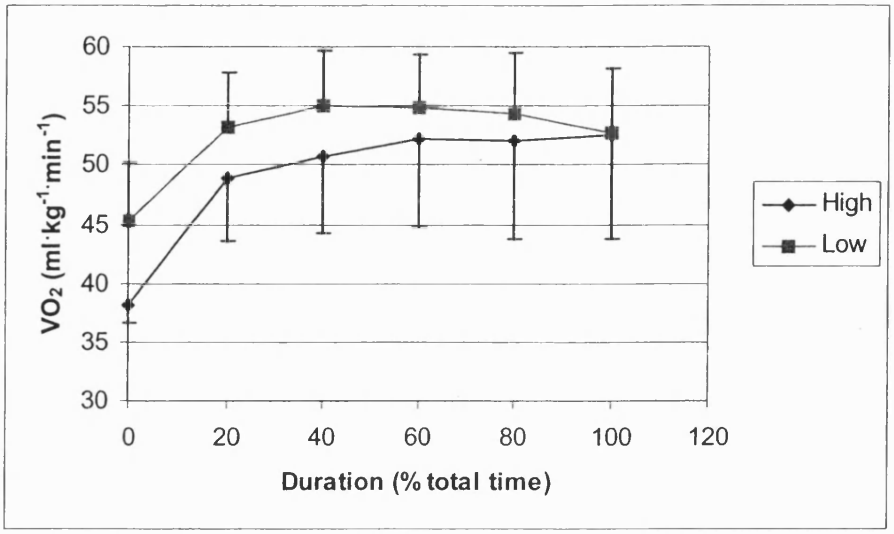


Figure 7.3.4. Mean (±SD) oxygen uptake ($\dot{V}O_2$) (ml·kg^{-1}·min^{-1}) for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

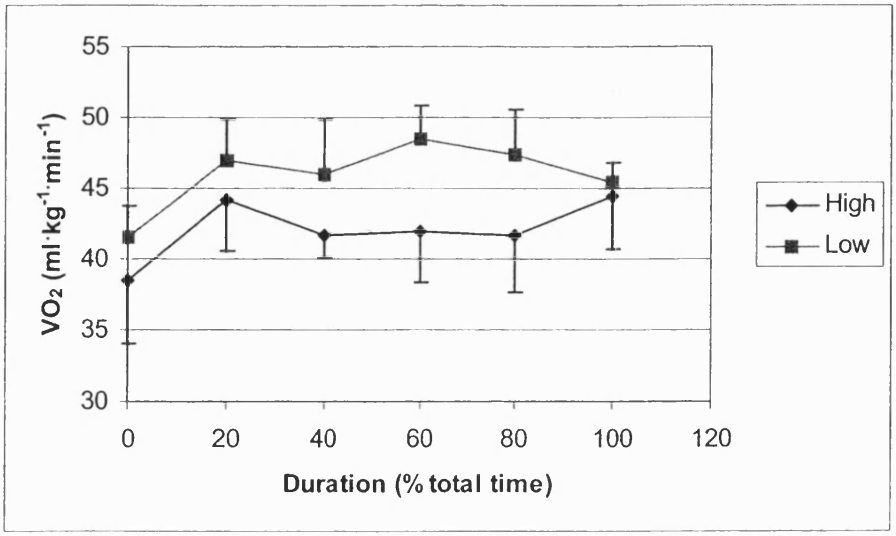


Figure 7.3.5. Mean (±SD) carbon dioxide production ($\dot{V}CO_2$) (ml·min^{-1}) for the duration of the 20 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

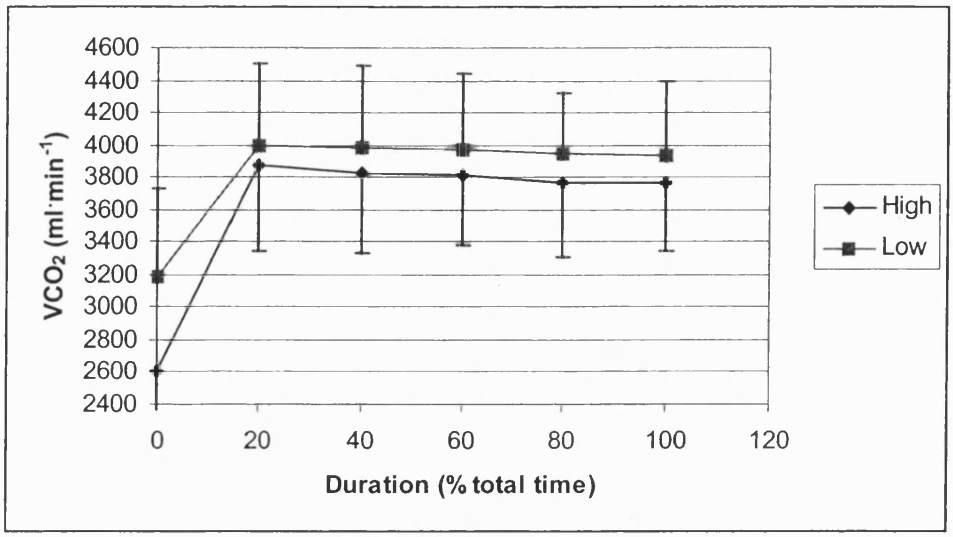
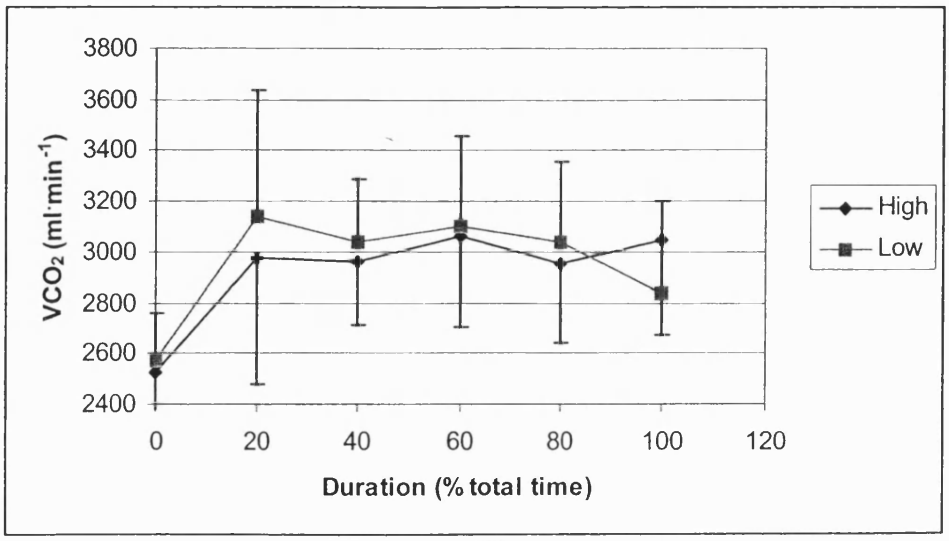


Figure 7.3.6. Mean (±SD) carbon dioxide production ($\dot{V}CO_2$) (ml·min^{-1}) for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.



With the exception of the first expired gas sampling point (0%), the RER was significantly ($p<0.01$) higher in the 20 min as compared with the 90 min trial. During the 20 min trial the RER was significantly ($p<0.01$) higher at all sampling points as compared with the first sampling point. During the 90 min trial this trend was not evident, with no significant differences found between the first point and the remaining gas sampling points. During the 20 min trial the RER of the subjects in the high LT group showed an increase in the early stages of exercise (between 20 and 40%) which was significant ($p<0.05$) (Figure 7.3.7). During the 90 min, the RER was similar in the early stages of the trial. However, after 20% of the trial, the RER increased in the high LT group relative to the low LT group. However, this was not a significant effect.

The oxidation rate of CHO ($g \cdot min^{-1}$) was higher than the rate of fat oxidation during the 90 min trial. However this was not significant. At the same time, there were no significant differences in the rate of CHO oxidation or the rate of fat oxidation between the subjects grouped in the high and low LT groups (Figure 7.3.9 to 7.3.10).

Figure 7.3.7. Mean (±SD) respiratory exchange ratio (RER) for the duration of the 20 min trial in the 'high' and 'low' LT groups. ** Significantly different from 'low' subjects'

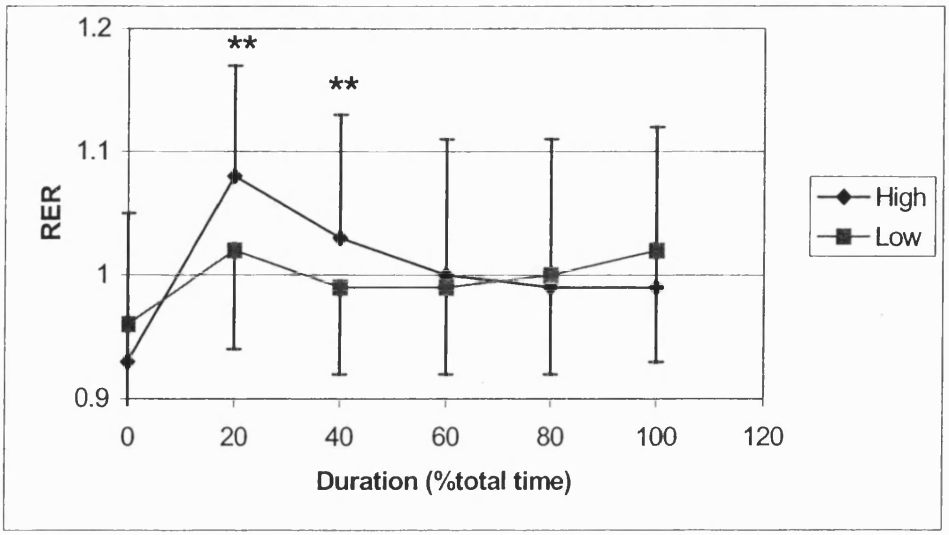


Figure 7.3.8. Mean (±SD) respiratory exchange ratio (RER) for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant differences between 'high' and 'low' subject groups.

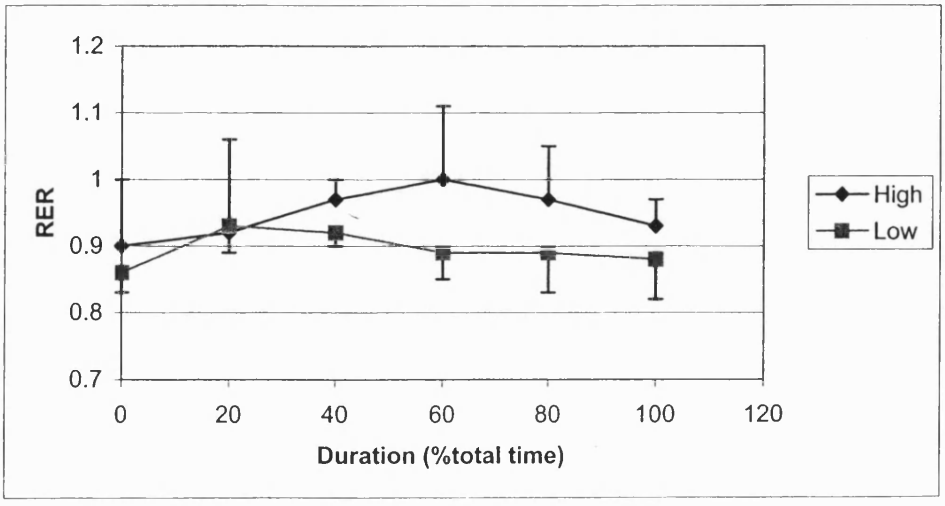


Figure 7.3.9. Mean (±SD) oxidation rate ($g \cdot min^{-1}$) of CHO for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant differences between 'high' and 'low' subject groups.

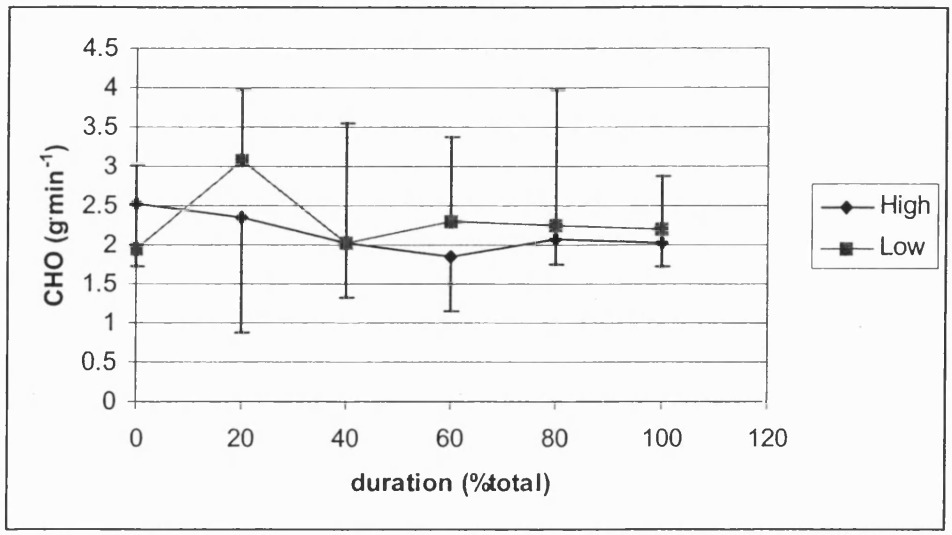
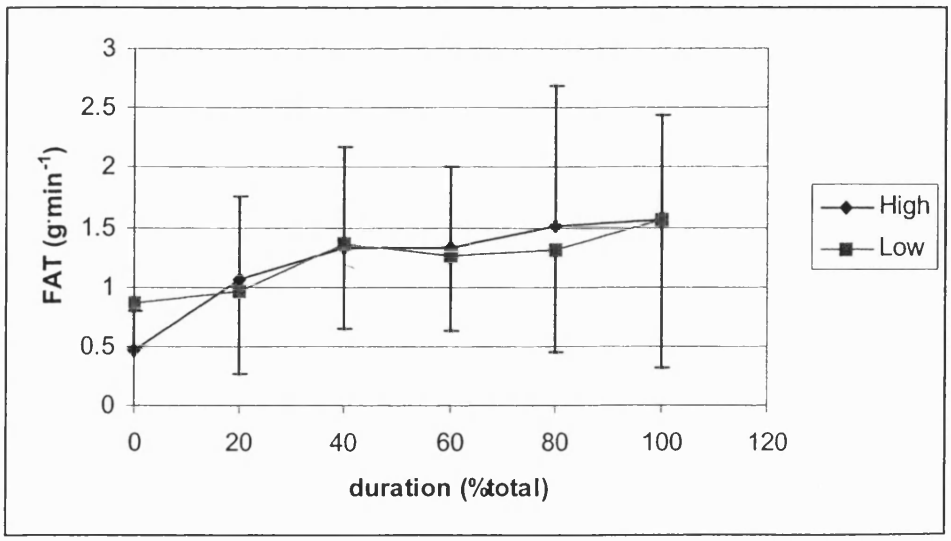


Figure 7.3.10. Mean (±SD) oxidation rate ($g \cdot min^{-1}$) of fat for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant differences between 'high' and 'low' subject groups.



The average HR (%HR_{max}) was not significantly different between the 20 min and 90 min trial. Whilst the HR (absolute and relative to HRmax) was generally lower in the 'high' group in both the 20 min and 90 min trial as compared to the 'low' group this was not significant.

Figure 7.3.11. Mean (±SD) heart rate (HR) (%HRmax) for the duration of the 20 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.

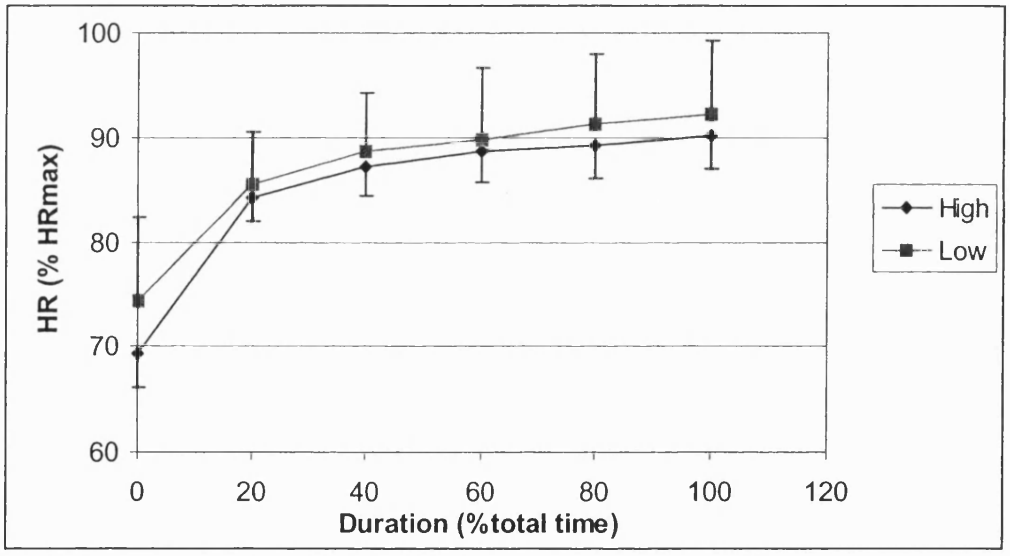
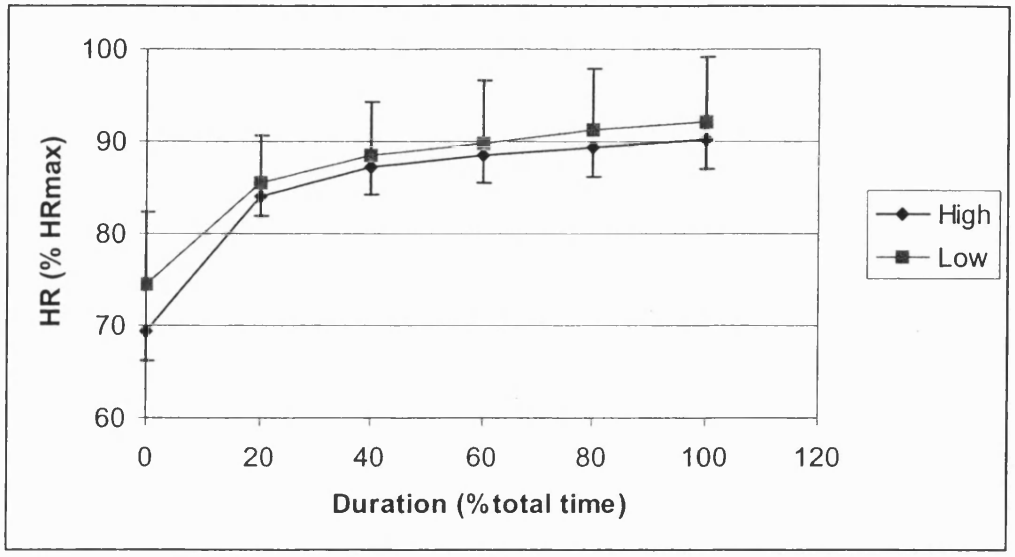


Figure 7.3.12. Mean (±SD) heart rate (HR) (%HRmax) for the duration of the 90 min trial in the 'high' and 'low' LT groups. No significant difference between high and low groups.



The blood lactate concentration (mM) was significantly ($p<0.01$) higher in the 20 min trial as compared with the 90 min trial at time points representing 40, 60, 80 and 100% of the total duration of each trial. Whilst the blood lactate concentration was significantly higher at all time points in both individual trials compared with pre, the appearance of lactate in the blood showed an exponential rise in the 20 min trial reaching a peak of ~7 mM at the end of the trial (Figure 7.3.13). In contrast, during the 90 min trial this variable remained relatively constant at ~ 3 mM (Figure 7.3.14). In both trials, there was a trend for the low LT subjects to show greater blood lactate accumulation at all time points except pre exercise (Figures 7.3.13 and 7.3.14). However, these differences were not statistically significant. There was no significant correlation between the post exercise

blood lactate concentration and the LT in the 20 min (r=-0.22) or the 90 min (r=0.07) trial.

Figure 7.3.13. The mean (±SD) blood lactate concentration during the 20 min trial in the high and low subjects. No significant difference between high and low subjects.

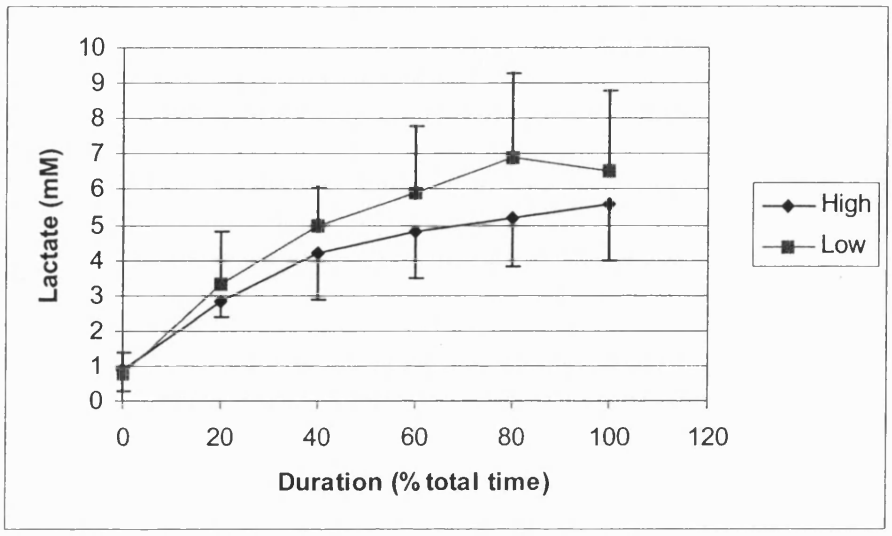
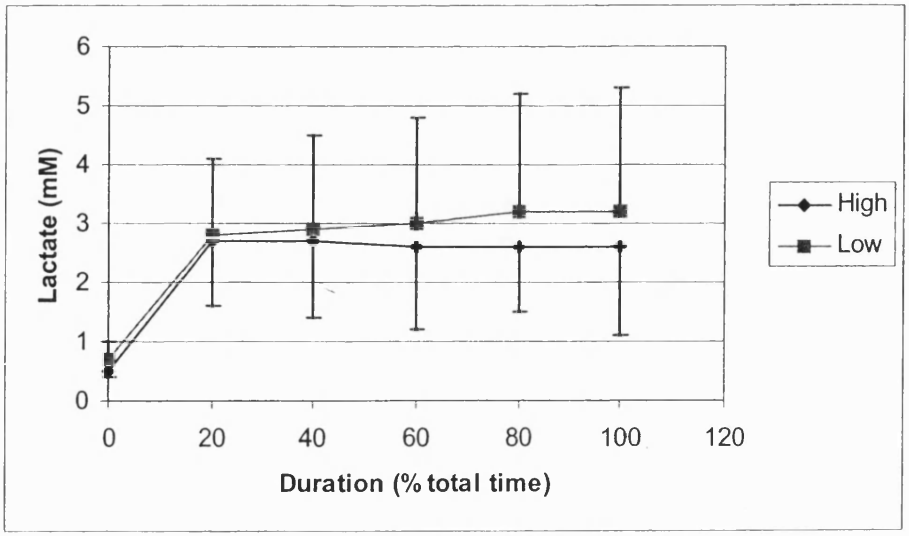


Figure 7.3.14. The mean (±SD) blood lactate concentration during the 90 min trial in the high and low subjects. No significant difference between high and low subjects.



Whole blood pH was not significantly different between the 20 min and 90 min trials. There were also no significant differences in this variable, at each sampling point in each exercise trial compared with the first (pre) sampling point. However, during the 90 min exercise trial, there was a trend for the pH to rise in the subjects in the high LT group after 60% of the trial relative to the low group. In accordance, the difference in pH between the high and low groups was significantly ($p<0.01$) different at sampling points corresponding to 80 and 100% of the trial. During the 20 min trial there were no significant effects of the subject group on pH during exercise.

Figure 7.3.15. The mean (±SD) blood pH during the 20 min trial in the high and low subjects. No significant difference between high and low subjects.

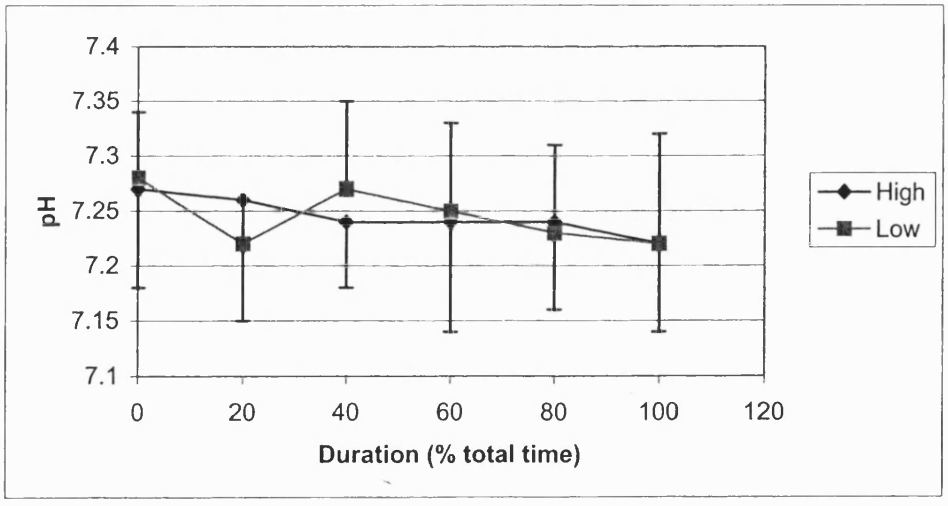
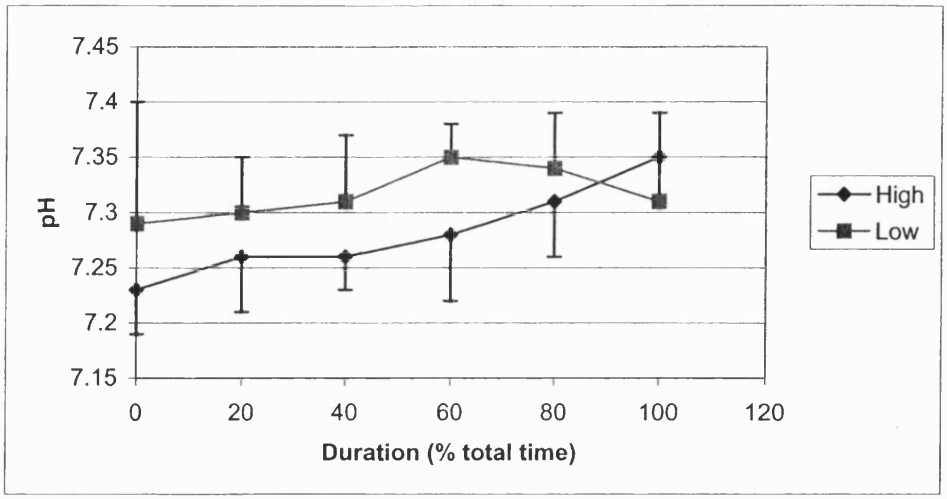


Figure 7.3.16. The mean (±SD) blood pH during the 90 min trial in the high and low subjects. No significant difference between high and low subjects.



Whole blood HCO_3 was significantly ($p<0.01$) lower at all sampling points in both the 20 min and 90 min exercise trials as compared with the first sampling point (pre exercise). In contrast to the 90 min trial, blood HCO_3 continued to decrease throughout the trial until completion when it was measured at ~ 15 mM. During the 90 min trial this variable initially decreased but then reached a plateau remaining at ~ 23 mM. There were no significant differences in HCO_3 in the subjects with high or low LT during either the 20 min and 90 min exercise trials.

Figure 7.3.17. The mean (±SD) blood bicarbonate (HCO_3) concentration (mM) during the 20 min trial in the high and low subjects. No significant differences between high and low subjects.

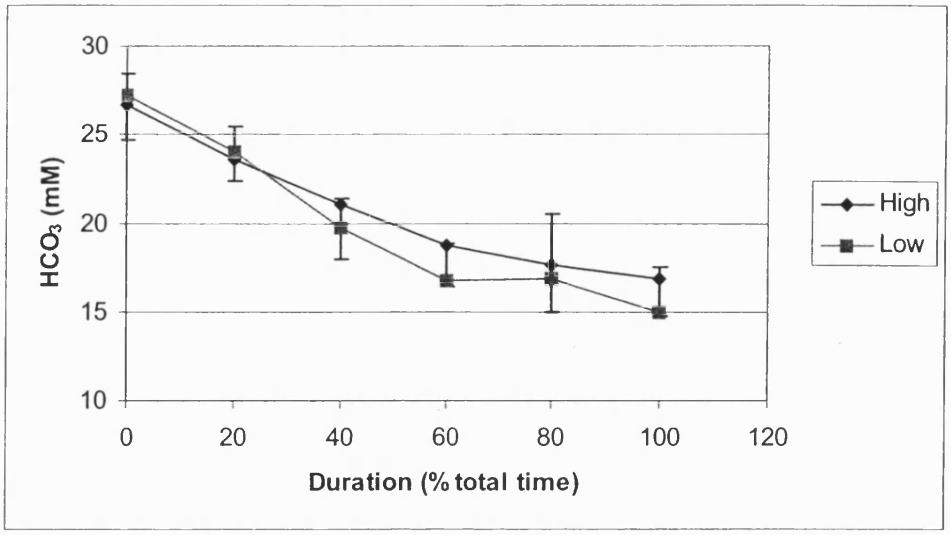
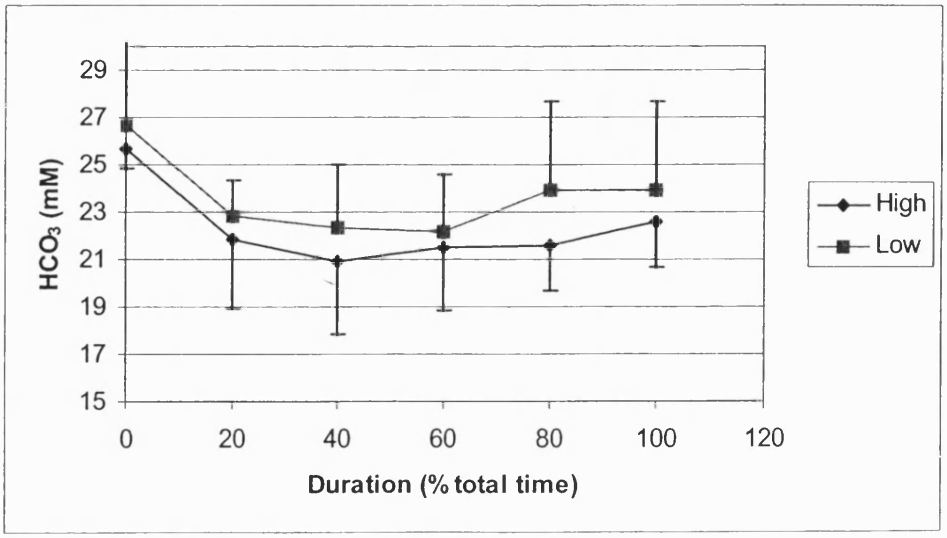


Figure 7.3.18. The mean (±SD) blood bicarbonate (HCO_3) concentration (mM) during the 90 min trial in the high and low subjects. No significant differences between high and low subjects.



7.4 Discussion

The aim of this experiment was to establish whether trained cyclists with similar $\dot{V}O_2max$, but differing LT (expressed as a % of $PPO_{3\ min}$) exhibited contrasting metabolic responses during a 20 min and 90 min set workload exercise trial. In general, those subjects possessing a high LT were shown to demonstrate slightly different responses to the endurance task compared with subjects with a lower LT. However, these differences were not significant.

An initial objective of the experiment was to recruit a population of well trained cyclists that were statistically similar in terms of $\dot{V}O_2max$ and PPO, but different in terms of their LT (%PPO). In this regard, the subjects in the high LT group possessed a $\dot{V}O_2max$ of ~ 60 $ml \cdot kg^{-1} \cdot min^{-1}$ and a LT of ~ 75%. In contrast, the low LT group had an inferior LT (~65%) but a similar $\dot{V}O_2max$. Indeed, the average workload for the 90 min trial (%PPO) was similar to the power output corresponding to the LT in the high group but significantly higher for the low group. Based on these results, it was expected that the subjects in the low LT group would demonstrate physiological responses indicative of greater metabolic stress during the exercise task. However, this was not the case, contradicting the hypothesis of the experiment.

There are a variety of studies that attempt to correlate the LT with endurance performance (Farrell et al., 1979; Miller and Menfredi, 1987; Bishop et al., 1998b;

Bentley et al., 1998). However, in these instances a 'cause and effect' scenario between the LT and endurance performance should not be concluded. There are a scarcity of studies that have compared the performance or physiological responses during an endurance task in subjects who differ in terms of the LT. Coyle et al. (1988) for example found that in a group of trained cyclists the time to fatigue at ~ 88% of $\dot{V}O_2$max was less, glycogen depletion, total CHO oxidised were higher and blood lactate accumulation greater in subjects with a lower LT. However, these researchers used a relatively short trial ranging from ~15 to 50 min. In contrast, in the present investigation, the blood lactate concentration in combination with whole body calorimetry was shown to be similar in both groups of subjects that possessed significantly different LT.

In explaining this result it is of interest to compare the LT of the subject groups in this study with the data of Coyle et al (1988). These subjects were reported to be 'elite'. However, the $\dot{V}O_2$max of the subjects in the present experiment were relatively similar. Indeed, more recent data suggests elite cyclists possess a $\dot{V}O_2$max of > 70 $ml \cdot kg^{-1} \cdot min^{-1}$ (Mujika and Padilla, 2001). The LT of the subjects in the low group of this study and that of Coyle et al. (1988) were similar. In contrast, however, the subjects in the high LT group in the study by Coyle et al. (1988) had a LT of > 85% as compared with 75% in this study. Whilst, the LT expressed in terms of PPO and $\dot{V}O_2$max has been shown to be similar in this experiment. The data reported by Coyle et al. (1988) was expressed relative to $\dot{V}O_2$max. This is a small, but possibly important difference. At the same time, closer examination of the data presented by Coyle et al. (1988) show a large

'physiological' gap (~10%) between the highest LT of the low group and the lowest of high group. In affect the subjects recruited for the present experiment probably would have been included in the low group as presented by Coyle et al. (1988). At the same time, whilst the LT of the high and low group were significantly different in this experiment, it is possible that the 'physiological difference' rather than the 'statistical difference', in these subjects was not great enough (~ 10%) to elicit any metabolic differences during the exercise trials. Therefore, it is possible that there is a minimum LT value (as a % of a maximal level) that results in greater metabolic and performance benefits, This area deserves further research, at the same time, if this hypothesis is correct, the implications are significant for talent identification in endurance sports. Future studies should look to examine the physiological responses to endurance exercise in populations of subjects with a LT of <65%, 65-75% and also >75 %. On this aspect, it is difficult to obtain subject populations of these dimensions especially in a group with an elevated $\dot{V}O_2max$. In fact, the high and low groups of subjects in this experiment had a similar LT in absolute terms (W). Therefore, whilst the subjects in the low LT group were exercising at higher relative (to PPO) intensity during the 90 min trial they were in fact exercising at the same absolute work rate. This may explain why no measurable differences were observed between the two groups. The data from this experiment showed a positive correlation between the LT in absolute terms and $PPO_{3\ min}$. This suggests that possibly the LT and $PPO_{3\ min}$ expressed in absolute terms shift in parallel with endurance training. More importantly, based on the results of this experiment it is likely that the LT expressed in absolute terms is more influential for endurance performance than that expressed as a % of a maximal level.

In another study, Coggan et al. (1992) demonstrated an greater increase in glucose uptake during endurance exercise in untrained subjects with a lower LT as compared to a group with a high LT. Whilst it is possible that a minimum LT value exists above which metabolic and performance benefits result, the data by Coggan et al.. (1992) indicates that it is possible for subjects possessing a LT of < 75% to exhibit different (and positive) metabolic responses to endurance exercise compared to subjects with a low LT (~65%). However, these authors used stable isotope tracer methods to track changes in glucose kinetics during exercise. Whilst glucose uptake as measured by stable isotopes are known to be related to glucose oxidation rates as measured by indirect calorimetry (Romijn et al., 1992), it is possible that the stable isotope studies are much more sensitive to examine glucose and fatty acid metabolism during endurance exercise. This in part may also explain why there were no significant differences in the metabolic responses to the exercise of the two groups of subjects investigated in this experiment.

The data from this experiment indicated a trend for the high LT subjects to exhibit lower metabolic responses to the endurance exercise. It could be argued that this small but non-significant difference was due to small subject numbers (n=12). However, the design of this experiment was based on two previous investigations (Coyle et al., 1988; Loftin and Warren, 1994). In the study by Loftin and Warren (1994) it was shown that subjects possessing a higher ventilation threshold (VT) (as measured by expired gas concentrations) performed better and exhibited lower metabolic stress to a 16.1-km laboratory time trial as compared to subjects who had a lower VT. The VT was not

measured in this experiment. However, other studies have shown that the workload corresponding to the VT and LT are relatively similar or are different depending upon the training status of subjects (Simon et al., 1986; Chicharro et al., 1997; Gaskill et al., 2001). Hence, it is not known if there was any difference in the workload corresponding to the VT and that of the LT. It is therefore possible that the VT is more sensitive for distinguishing the metabolic responses to endurance exercise. However, this remains to be investigated.

Regardless of whether the subject numbers were limited or not, it was expected with similar subject numbers to the two previous studies (Coyle et al., 1988; Loftin and Warren, 1994), there would be a significant metabolic difference if the LT was significantly different in the two groups. Future studies may wish to repeat this experiment with large subject numbers but also include more invasive methodology such as stable isotope tracing techniques.

One contrasting influence in this experiment and that of the two other studies is that these authors used time trials. In the current experiment, a set workload trial was used at a similar average power output to the time trials performed in experiment three. This procedure was thought to be appropriate for examining the metabolic responses in the two groups during prolonged exercise. It has also been used in other studies with a similar research purpose (Coyle et al., 1988). However, effectively this is not a time trial and this is possibly one reason why there were no detectable differences in the responses to the exercise trials in the two groups. There are recent studies that have examined

'pacing' strategies during cycling time trials (Mattern et al., 2000; Nikolopoulos et al., 2001). It is possible that a set workload trial does not simulate the metabolic demands of a real time trial. In this regard, it is possible that it is the ability to change to an excessively higher intensity for longer periods whilst maintaining a constant power output between these periods of intensive effort during endurance competitions is that which distinguishes good and bad time trial performers. This in turn may explain why no differences were found in the two groups of subjects during the set workload trials in this experiment.

In conclusion, the results of this study show that in well-trained cyclists with similar maximal physiological characteristics, the LT expressed as a percentage of PPO obtained from an incremental exercise test does not differentiate the metabolic responses to a endurance task of either long or short duration.

CHAPTER EIGHT

GENERAL DISCUSSION AND CONCLUSIONS

CHAPTER EIGHT – GENERAL DISCUSSION AND CONCLUSIONS

8.1 General Discussion

In this thesis, a number of studies concerning the validity of PPO, the LT and OBLA in endurance athletes have been presented. The main objective of the research was to obtain a better insight into the relevance to performance of current methods of physiological analysis of endurance cyclists. The main methodological issues and physiological variables associated with endurance performance were first highlighted in a review of the literature to date. The main points raised were that, firstly, there is considerable evidence suggesting that the physiological results of incremental exercise testing are affected by the choice of protocol. Secondly, there has been little analysis of the relevance of the PPO, LT and OBLA to long or short duration endurance performance. The proceeding four chapters then presented data on four individual experiments relevant to the areas outlined in the literature review. In experiment one, the LT and OBLA obtained from two separate incremental exercise testing protocols were compared. The main results that the power output (W) was significantly lower in an incremental exercise test comprising stages of 8 min duration than from a 3 min stage test. However, this result was only evident in well trained subjects. The power output (%PPO) was also significantly higher in an incremental test comprising stages of 3 min duration compared to one with stages of 8 min duration. In experiment two, the PPO, LT and OBLA obtained from two incremental exercise tests comprising stages of 3 and 5 min duration respectively were compared in well trained cyclists. However, no significant differences were found for these variables between tests. On the basis of these two experiments, in experiment three

an incremental exercise comprising stages of 3 min duration was administered to a group of well trained cyclists in combination with a 90 min and 20 min cycling time trial. This experiment demonstrated that the relationship between PPO, LT and OBLA may change depending upon the duration of an endurance performance task. However, the LT and PPO was found to be the variable that most correlated with 90 min cycling performance. In the final study, the metabolic responses during a 20 min and 90 min set workload trial were compared between two groups of well trained cyclists with different LT. However, in general, no significant differences were found between cyclists with 'high' and 'low' LT, on this basis. Therefore, the LT was not a variable that could be used to distinguish exercise metabolism in these tasks. The objective of this final chapter is to summarise and offer general conclusions on the data (and discussion points) here presented in the four experimental studies, as well as suggest possible avenues of future research.

It is of paramount importance for research physiologists and applied sport scientists working with endurance athletes, to understand the validity of the variables they are measuring and also to understand the consequences of choosing to implement a particular incremental exercise protocol. Whilst it is common for researchers and applied scientists alike to use incremental exercise testing, there are a variety of approaches and protocols for determining many physiological parameters. Each incremental exercise protocol has the possibility of influencing the value obtained for the physiological variable that is being examined. This in turn may affect the purpose of measuring such variables. The data from the first two studies of this research indicate that in cyclists ranging from recreational level to well trained, an incremental test protocol comprising stages of 3 min

duration is all that is required to measure maximal ($\dot{V}O_2$max, PPO) and submaximal (LT and OBLA) physiological variables. However, the results from experiment one demonstrate that the training status of subjects may influence the workload corresponding to the LT during a prolonged, more submaximal test comprising stages of 8 min duration. At the same time using stages of longer than 3 min duration (in combination with an initial test to determine PPO or $\dot{V}O_2$max) may influence the OBLA expressed as a % of PPO. Therefore, exercise physiologists possibly should consider the effects and possible implications of implementing different incremental exercise protocols when examining well-trained athletes. However, in experiment two is was shown there were no differences in the LT or OBLA between a 3 min and a 5 min stage test both of which are appropriate for measuring the PPO. These findings aside, the physiological mechanisms surrounding the difference in the LT measured from the 3 min and 8 min stage test in the well-trained subjects were not investigated. It is possible this may provide greater information relevant to the differences observed in this experiment. At the same time, an approach to understanding the mechanisms surrounding the LT may provide information concerning the adaptation of this variable with endurance training.

The appearance of blood lactate is known to be a combination of both metabolic production and elimination (Wasserman et al., 1986; Stallknecht et al., 1995). MacRae et al. (1992) demonstrated that when exercise is performed at different exercise intensities relative to $\dot{V}O_2$max, the ratio of lactate production and elimination of lactate (as measured by stable isotope studies) may change following short term training interventions. The mechanisms behind the reduction in the LT with the longer stage (8

min) test observed in this thesis may be in part associated with these differences in lactate production or clearance in well trained or not so well trained subjects. The biochemical mechanisms in skeletal muscle surrounding the actual production or elimination of lactate and associated metabolic end products are diverse and may reflect skeletal muscle enzyme activity or lactate transport capacity (Stallknecht et al., 1995; Juel, 2001). In one study, Ivy et al. (1980) found that in untrained subjects performing cycle ergometer exercise the LT was correlated to the muscle oxidative capacity. More recently, Bishop et al. (2000) found that in female cyclists of mixed ability level, muscle capillarisation around FT fibres (measured by histochemical techniques) was correlated to the LT. These authors concluded that the increase in capillarisation around the more glycolytic fibres resulted in greater lactate dissipation and this in turn was why the correlation was observed between this variable and the LT. Indeed, Coyle et al. (1988) have identified that muscle capillarisation changes the relationship between the LT and the appearance of blood lactate during prolonged exercise in trained subjects. Therefore, it is possible that in well trained subjects the reduction in the LT was due to a combination of physiological factors influencing lactate production or elimination by skeletal muscle.

The production of lactate by skeletal muscle is associated with the activity of a number of enzymes including those within the pyruvate dehydrogenase complex (Constantin-Teodosiu et al., 1991). At the same time, it has recently been shown that monocarbylate transporters necessitate lactate diffusion as opposed to simple passive diffusion (Bonen, 2001). This in turn may result in greater oxidation of lactate in non-active tissue. Therefore, the adaptation of these processes may be significant in terms of measuring the

LT and work rate corresponding to set lactate concentrations such as the OBLA. Therefore, it would seem that a number of mechanisms may be associated with the LT (and related physiological variables) determined from a number of different incremental exercise protocols. Further studies are required to elaborate further the effect of different incremental exercise protocols on the LT and related physiological variables and how the characteristics of skeletal muscle influence these results.

The physiological results such as the LT and OBLA obtained during incremental exercise testing are used to quantify adaptation to endurance training, to prescribe endurance training by establishing exercise training work rates or to correlate with endurance performance (Bishop et al., 1998b; Lucia et al., 2000; Stepto and Hawley, 1999). The results of experiment three indicate that the LT and PPO were correlated to the average power output during a 90 min cycling time trial. However, the practical implications of the difference in the LT and OBLA obtained from the 3 min and 8 min stage incremental test found in experiment one were not investigated. The work rate corresponding to the LT can be typically maintained for ~ 2 hrs (Farrell et al., 1979). It is for this reason that endurance running coaches prescribe this variable for training of marathon specialists (Coyle, 1995). If an exercise physiologist or coach were to recommend to an athlete to exercise at a work rate on the basis of either the results of the 3 min or 8 min protocol, it may change the metabolic responses and fatigue manifestation during exercise at that work rate. Further investigations are required to establish the different metabolic responses to prolonged exercise at the LT determined from the results of the 3 min stage or 8 min stage test. Furthermore, it has recently been shown that the metabolic responses

at the same relative work rate are different between running and cycling (Arkinstall et al., 2001). A further extension of this work would be to examine the metabolic responses to the different incremental exercise protocols (3 or 8 min stage) and to set work rate exercise at the LT determined from either of these tests. Another possible implication of the results of experiment one is that although numerous studies have demonstrated a positive correlation between the LT and endurance performance (e.g. Bishop et al., 1998b), because the LT may change depending upon the incremental test, the correlation of this variable to endurance performance may also change. Therefore, the predictive power of these variables and endurance performance may change depending upon the test completed to measure these variables.

It is widely accepted that skeletal muscle positively adapts to endurance training (Holloszy and Coyle, 1984). Endurance training can be a combination of low intensity, prolonged exercise or high intensity interval type training. Typically, performance changes are observed when the general intensity of training increases (Mujika et al., 1995; Steinacker et al., 1998). The mechanisms surrounding the adaptive response to higher intensity training has only recently been investigated. Westgarth-Taylor et al. (1997) have shown, for example, that the blood lactate response, as well as CHO oxidation rate, is lower at the same absolute exercise intensity during an incremental task after a period of higher intensity interval training in already well trained subjects. However, in another study, a similar period of training resulted in no change in muscle oxidative capacity, but an increase in PPO, which was associated with improved muscle buffering capacity (Weston et al., 1997). Therefore, there are a number of studies that

demonstrate positive changes in the blood lactate response to incremental exercise, but in similar situations the oxidative capacity of muscle remains unchanged. Hence, despite the fact that the LT is known to be related to muscle oxidative capacity, the muscle physiological variables associated with the LT and the effect of training response to both factors is not fully understood. The LT is usually quantified to establish the adaptive response to endurance training (Lucia et al., 2000). Future studies should look to examine the change in the LT determined from different incremental exercise protocols in combination with skeletal muscle plasticity in response to different endurance training interventions. Furthermore, in experiment three it was concluded that short endurance performance may have different physiological demands to longer endurance tasks. Some of the factors in skeletal muscle include cappillarisation and buffer capacity both influencing lactate metabolism (Coyle et al., 1988; Coyle et al., 1991; Weston et al., 1997; Bishop et al., 2000). However, these studies did not compare a long and short endurance task. Therefore, the characteristics of skeletal muscle associated with long and short endurance performance should be examined in future research studies.

It is widely purported, most recently by Coyle, (1995) and Basset and Howley (2000) that a high LT is necessary for successful endurance performance. However, how significant is the LT in terms of endurance performance and how does this variable change with endurance training? Coyle (1995) has suggested endurance performance or 'performance velocity' is associated with the 'performance $\dot{V}O_2$' and 'performance power'. The data from experiment three examined the relationship between the LT, the OBLA and these variables. The data indicates that other physiological factors may dictate these

'performance' parameters during an endurance competition situation. Exercise efficiency for example has been presented as another variable that distinguishes performance in an endurance event (Basset and Howley, 2000). Cycling efficiency was not investigated in this research. Therefore, it would be of interest to examine the relationship of this variable to long and short endurance performance. The data from this research also indicates that endurance performance is multi factorial. It should not be perceived that one key physiological variable is more indicative of endurance performance or is able to differentiate the metabolic response to an endurance task as opposed to another. This is especially relevant when endurance tasks of long or short duration are examined.

Recently there has been an interest in neurological factors that relate to fatigue during endurance exercise (Paavolainen et al., 2000; Bentley et al., 2000; St Clair Gibson et al., 2001; Lepers et al., 2002). Lepers et al. (2002) for example demonstrated a decrease of 8% in muscle activation during a 5-hr cycling task in trained subjects. Other workers have concluded that both peripheral metabolic or central neural fatigue processes are uncoupled during fatigue in endurance cycling tasks (Bentley et al., 2000). This is especially true in cycling as this activity is unique in terms of pedalling cadence which may demonstrate different fatigue responses during prolonged exercise at higher or lower pedalling frequency (Lepers et al., 2001) Therefore, in well trained subjects with similar 'physiological characteristics' obtained from incremental exercise testing, the neurological response may be an important consideration in terms of performance as opposed to traditional physiological/metabolic parameters obtained from an incremental exercise test. Examining the neural adaptations during endurance cycle activity

may be necessary to investigate on the influence this has on performance.

The point should also be raised concerning the real validity of the performance tasks completed by subjects in this research. Firstly, the performance tasks were completed within a laboratory setting without the environmental influences usually associated with performance in the field. This in itself is very distant from that which occurs in the field. Balmer et al. (2000a) have shown that the PPO obtained during an incremental exercise test is not correlated to the 'performance velocity' associated in a cycling time trial. Therefore, whilst the experiments presented in this thesis have modelled endurance performance in terms of the average power output observed during exercise, an elevated power output may not transfer to performance velocity in the field. An elevated 'performance power' can only be viewed as positive in the context of endurance sports. Therefore, the physiological factors related to this can also be viewed as important in the analysis of the endurance athlete.

As previously mentioned the anthropometrical characteristics including body mass and projected frontal area are highly influential for the reduction of frontal resistance during cycling (Olds, 2001). Other researchers have demonstrated a positive correlation between body mass and the time taken to complete a 40-km time trial in trained subjects (Swain, 1994). Therefore, whilst the LT may be influential in the average power sustained for the duration of a endurance cycling trial it may be that other factors influencing locomotion in combination with geographical characteristics may influence performance velocity. The fact that the power output corresponding to the LT was highly related to the power

output during the 90 min time trial observed in experiment three is justification enough for inclusion of his variable in a endurance performance assessment. However, a holistic approach should be taken in terms of optimising and assessing the physiological and biomechanical factors associated with performance.

Endurance competitions are diverse. Therefore, as presented in this thesis improving one physiological parameter may not be applicable to a particular event as opposed to another. Indeed, there are specific factors in different endurance events, which may dictate overall performance. Cycling was chosen as the activity for analysis in this series of studies because it is common to a number of different sports. For example, the cycling stage of a triathlon ranges between 20 and 180-km. In the sport of road cycling, time trials are held between 8 and 60-km. Furthermore, the usual stage road racing events are anywhere between 100 and 200-km. Mountain cycling is held over a similar duration to triathlon but obviously in undulating off road terrain. In track cycling there are a diversity of events ranging from very short 'sprint' to longer 'points' racing. Therefore, there is great diversity in the physiological characteristics of each competition. Hence, these characteristics should be considered before an appropriate physiological diagnostic procedure is established for a particular endurance athlete.

In track cycling it has been shown that there is large anaerobic component to performance (Craig et al., 1989; Craig and Norton, 2001). Anaerobic performance is typically associated with strength and power manifestation (Murphy and Wilson, 1997). However, another study has demonstrated that muscular strength and power is not associated with

PPO and the Dmax lactate threshold (Bentley et al., 1998). Therefore, the results of the data in this thesis may not be applicable to specialist track cyclist, but more relevant for a endurance track cyclist or road cyclist specialising in time trial events.

In triathlon there are many specific factors influencing performance and metabolism in this sport (Bentley et al., 2002). The published review (Bentley et al., 2002) appearing in this thesis (See following 'literature review') outlines these factors. Briefly, however, cycling must be performed after swimming and running after cycling. There is evidence demonstrating a negative affect of the preceding disciplines on subsequent exercise performance in a triathlon (Bentley et al., 2002). Indeed, it has been suggested that the ability to link the 3 disciplines may be important for overall triathlon performance (Millet and Vleck, 2000). The physiological variables obtained in the incremental tests used in this experiment (in particular the LT and PPO) maybe useful in correlating with power output sustained over a particular duration. This in turn, is important for quantifying training adaptation. However, in terms of prediction of performance in triathlon, physiological variables such as the PPO and LT obtained from a single incremental exercise test may not be as applicable because of the residual fatigue observed between stages in this event. Indeed, two different research groups have shown that more specific physiological testing procedures involving running tests after cycling and swimming maybe more appropriate for monitoring triathletes (De Vito et al., 1995; Millet et al., 2000). Physiologists working with triathletes or specific endurance populations should consider the specific requirements and characteristics of a particular sport before implementing a specific physiological testing battery.

8.2 Implications and conclusions

One of the main findings of this research is that the dimensions of an incremental exercise protocol influences the work rate corresponding to the LT and OBLA. This has implications for the exercise physiologist in terms of performance evaluation and endurance training prescription. Firstly, if a physiologist were to recommend training at the work rate corresponding to the LT and OBLA, quantifying this from two different exercise tests may give contrasting results. This in turn may influence the metabolic responses to training at that workload. This research did not investigate the impact that the differences in the LT and OBLA from the different exercise tests has in terms of correlating with endurance cycling performance and the responses of these variables to endurance training. However, the implication is that the results of different incremental exercise tests may influence the predictive power of the LT and OBLA and endurance performance. It is also not known whether the results of one test or another are more sensitive to endurance training.

A second finding from this work is that the PPO and LT significantly correlated to 90 min cycling performance but not shorter 20 min performance. It is clear from this data that physiologists working with cycling and triathlon should consider the metabolic demands of events of different duration and intensity. The LT and PPO should be viewed as key variables responsive to endurance training programs. However, it is possible that the LT and OBLA may not reflect performance in cycling time trial performance of different duration.

This research further demonstrates that an incremental test comprising 3 min stages is optimal for measuring the PPO, the LT and OBLA in well trained cyclists. In contrast, the LT may not be sensitive enough to distinguish the physiological responses to prolonged endurance exercise. This final area of work requires further investigation using more invasive methodology for studying exercise metabolism.

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CHAPTER NINE – REFERENCES

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APPENDICES

in experimental design, training practice and also performance diagnosis of triathletes.

1. The Sport of Triathlon

Triathlon is a unique endurance sport that comprises a sequential swim, swim-to-cycle transition, cycle, cycle-to-run transition, and run over a variety of 'long' or 'short' distances (table I). With exception, triathletes are successful in either short- or long-distance triathlon competitions. In both long- and short-distance events, competition is held between 'elite' and 'age-group' athletes. Elite athletes are defined as those holding an International Triathlon Union (ITU) world ranking of <125. Age-group athletes compete against each other in 5-year age categories. Average completion times over the various race distances for both elite and age-group competitors of similar age, that is, in the 20- to 24-year-old category are shown in table II for males and table III for females, respectively.

Triathlon events have distances in common with individual distance swimming, time-trial cycling and distance-running competitions. However, triathlons are typically conducted under different environmental, tactical and technical conditions. Unlike pool-based swimming competitions, triathlon swims usually take place in a river, a lake or the sea. They commonly involve separate mass starts of up to 300 athletes. In contrast to the relatively uniform conditions experienced in pool-based swimming competitions, triathlons are raced under varying conditions of water salinity, turbulence and temperature. When water temperature is below 14°C, but not over 21°C, athletes may wear wetsuits of up to 5mm thickness. The wetsuit may be made of one or two pieces, have either long or short sleeves, long or short legs, and is with or without a cowl.

Table I. Triathlon race distances (km)

Event	Distance	Swim	Bike	Run
Long	Ironman	3.8	180	42
	Middle distance	2.5	80	20
Short	Triathlon[a]	1.5	40	10
	Sprint	0.75	20	5

a Previously known as Olympic or Classic distance.

Drafting involves completing physical activity behind another athlete completing the same activity in a 'sheltered' position. Drafting is allowed within the swim section of all triathlons, regardless of event distance or athlete ability. However, only elite triathlon-distance (senior and junior) athletes may draft during the cycle leg. Drafting is not legal within age-group competition. Therefore, age-group athletes are expected to complete the cycle stage as an individual time trial.

The physical and physiological characteristics of triathletes have been largely identified and reviewed.[1-4] This review addresses the specific technical aspects of triathlon and the effect that these characteristics have on exercise metabolism during a triathlon event. Particular focus will be the use of wetsuits in swimming, drafting during swimming and cycling as well as the effects of prior physical activity on cycling or running performance.

2. Specific Physiological Demands of Triathlons

2.1 Swimming

2.1.1 The Effects of Wearing a Wetsuit on Swimming Performance

The regulations regarding the use of a wetsuit in a triathlon event are very precise at an international level. In standard-distance races, wearing a wetsuit is compulsory when the water temperature is below 16°C and forbidden when the water is warmer than 20°C. At the same time, the thickness of the fabric that is used to make wetsuits can not exceed 5mm. This ruling has been implemented in an attempt to limit the buoyancy advantage provided by the wetsuit.[5] Recently, many wetsuit producers have proposed various wetsuit models designed with one or two pieces, with long or short

Table II. Average race completion times (h:min:sec) at the 2001 International Triathlon Union World Championships for the top 10 elite and 20- to 24-year-old age-group (AG) male triathletes (data down to 50th finisher not available for all groups) in Ironman and triathlon distance events (draft-legal for elite athletes and non-drafting for AG in standard distance cycle competition)

Distance	Swim		Cycle		Run		Overall	
	elite	AG	elite	AG	elite	AG	elite	AG
Ironman	0:51:10 ± 0:01:40$_x$ [a]	1:01:11 ± 0:05:39$_x$ [b]	4:43:05 ± 0:04:39$_x$ [a]	5:13:09 ± 0:14:11$_x$ [b]	2:53:52 ± 0:04:19$_x$ [a]	3:32:00 ± 0:18:42$_x$ [b]	8:31:09 ± 0:05:06$_x$ [a]	09:52:00 ± 0:31:39$_x$ [b]
Triathlon (senior)	0:18:21 ± 0:00:14$_y$ [a]	0:19:11 ± 0:01:12$_y$ [b]	0:56:53 ± 0:00:17$_y$ [a]	1:00:09 ± 0:01:20$_y$ [b]	0:32:01 ± 0:00:22$_y$ [a]	0:36:52 ± 0:01:17$_y$ [b]	1:48:33 ± 0:00:49$_y$ [a]	2:00:33 ± 0:01:41$_y$ [b]
Triathlon (junior)	0:19:11 ± 0:00:30$_z$ [a]	0:18:47 ± 0:00:50$_y$ [b]	0:58:09 ± 0:00:29$_z$ [a]	1:00:23 ± 0:00:13$_y$ [b]	0:33:52 ± 0:00:40$_z$ [a]	0:37:35 ± 0:01:20$_y$ [b]	1:52:33 ± 0:00:41$_z$ [a]	2:01:23 ± 0:02:32$_y$ [b]

Different superscripts (**a** and **b**) indicate significant ($p < 0.01$) difference (elite *vs* AG) in each discipline (swim, cycle, run) and overall at the 95% confidence level; different subscripts (**x**, **y** and **z**) indicate significant ($p < 0.01$) difference [Ironman *vs* standard (senior) *vs* standard (junior)] in each discipline (swim, cycle, run) and overall at the 95% confidence level.

sleeves, long or short legs, and with or without a cowl. However, the performance benefits of these different wetsuit types are relatively unknown.[6]

Wearing a wetsuit maybe useful in cold water, especially in long-distance swimming, to reduce the incidence of hypothermia. However, it has been suggested that when a wetsuit is used, body core temperature may rise, thus affecting performance.[7] Nevertheless, a number of researchers[8,9] have found no detrimental effects when athletes wear wetsuits in water that is 17 to 29.5°C.

Typically, middle-distance swimming is a function of both aerobic capacity and exercise efficiency.[10] At the same time, there are a variety of parameters that scientists have used to examine the factors associated with swimming performance.[11] For example, the hydrostatic lift during swimming, together with improved buoyancy are known to be associated with successful swimming performance.[12,13] A number of these factors have also been examined when a wetsuit has been used during swimming activity in triathletes and competitive swimmers.[5,14] The most important effect of using a wetsuit is for velocity to increase, and this is caused by gains in both buoyancy and hydrostatic lift.[15] Chatard et al.[5] for instance, examined the time (minutes) taken to swim 400m by competitive swimmers and triathletes who were wearing either a wetsuit or standard swimming trunks. Triathletes swimming 5 minutes 07 ± 30 seconds for 400m, improved 22 seconds or 30m when a wetsuit was used. Competitive swimmers completing 400m in 4 minutes 12.5 ± 7 seconds did not improve. However, those athletes swimming 4 minutes 39 seconds improved 12 seconds when wearing a wetsuit.[5] The changes in 400m swim time when a wetsuit was used were correlated ($r = -0.63$; $p < 0.05$; $n = 16$) to changes in hydrostatic lift and buoyancy. Passive drag can be calculated by having a swimmer pulled ('passively') along in water using a winch system connected to a load cell.[12] Passive drag has been shown to decrease by 9 to 20% when a swimmer is wearing a wetsuit.[5] In another study, Cordain and Kopriva[16] reported that compared with standard swimming trunks, buoyancy was improved by wearing a full-body sleeveless triathlon wetsuit, resulting in an improvement in 1500m performance. The body density while wearing the wetsuit was inversely related to performance over 400m ($r = -0.46$; $n = 14$) and over 1500m ($r = -0.54$; $n = 14$). Toussaint et al.[14] also showed a 12 to 16% decrease in active drag when individuals swam in a wetsuit. However, other researchers[17] have shown no difference in the hydrodynamic coefficient (Cx) of individuals swimming in a wetsuit compared with without one.[17]

It is likely that the potential performance gain to be had from wearing a wetsuit is affected by the velocity at which the swimming event is con-

Table III. Average race completion times (h:min:sec) at the 2001 International Triathlon Union World Championships for the top 10 elite and 20- to 24-year-old age-group (AG) female triathletes (data down to 50th finisher not available for all groups) in Ironman and triathlon distance events (draft-legal for elite athletes and non-drafting for AG in standard distance cycle competition)

Distance	Swim		Cycle		Run		Overall	
	elite	AG	elite	AG	elite	AG	elite	AG
Ironman	0:58:02 ± 0:03:55$_x$ [a]	1:19:07 ± 0:12:24$_x$ [b]	5:25:38 ± 0:09:24$_x$ [a]	6:20:00 ± 0:35:56$_x$ [b]	3:25:35 ± 0:10:19$_x$ [a]	5:03:39 ± 0:44:34$_x$ [b]	9:53:54 ± 0:13:46$_x$ [a]	12:51:12 ± 1:11:51$_x$ [b]
Triathlon (senior)	0:19:21 ± 0:00:19$_y$ [a]	0:21:11 ± 0:01:27$_y$ [b]	1:03:11 ± 0:00:22$_y$ [a]	1:07:09 ± 0:01:36$_y$ [a]	0:36:28 ± 0:00:45$_y$ [a]	0:39:52 ± 0:01:01$_y$ [b]	2:01:15 ± 0:01:54$_y$ [a]	2:11:33 ± 0:02:47$_y$ [b]
Triathlon (junior)	0:20:11 ± 0:00:35$_z$ [a]	0:21:38 ± 0:01:11$_y$ [b]	1:05:09 ± 0:00:36$_z$ [a]	1:11:30 ± 0:02:05$_z$ [b]	0:38:52 ± 0:00:20$_z$ [a]	0:44:46 ± 0:02:30$_z$ [b]	2:05:33 ± 0:00:45$_z$ [a]	2:21:09 ± 0:02:38$_z$ [b]

Different superscripts (**a** and **b**) indicate significant ($p < 0.01$) difference (elite *vs* AG) in each discipline (swim, cycle, run) and overall at the 95% confidence level; different subscripts (**x**, **y** and **z**) indicate significant ($p < 0.01$) difference [Ironman *vs* standard (senior) *vs* standard (junior)] in each discipline (swim, cycle, run) and overall at the 95% confidence level.

ducted. Most studies have examined the performance improvements when participants wore a wetsuit over shorter distances (e.g. 400m) where swimming velocity is greater relative to that in a standard-distance triathlon. De Lucas et al.[17] showed a smaller performance improvement over 1500m (3.7%) in triathletes and swimmers who averaged 1.17 m/sec than Lowdon et al.[8] found in triathletes swimming at 0.90 m/sec (10%). Velocity is lower during the swimming stages of longer distance triathlon events. Therefore, it is likely that the change in velocity with different length swimming will result in a change in the physiological benefits when athletes wear a wetsuit during swimming. Thus, performance benefits may not be as great in the longer distance triathlons.

The potential combination of different wetsuit specifications (short or long legged; short and long sleeved) coupled with the individual physical characteristics of an athlete, is great. Indeed, it has been suggested that the wetsuit design in combination with the physical characteristics of a swimmer may influence the change in swimming performance obtained when using a wetsuit.[15] However, future studies should look to examine this area more extensively. That aside, it is now widely accepted that wetsuit use during the swimming section of a triathlon leads to reductions in energy cost and gains in performance, through improvement in buoyancy and reductions in drag.[5,6,8,15-19] At the same time, the extent to which the positive changes in both hydrodynamic lift and drag that are incumbent when wearing a wetsuit, are also related to the technical ability of the athlete. Slower athletes are usually more immersed in water and will benefit more, by improvements in horizontal body position provided by a wetsuit.[5] When compared with highly skilled swimmers, triathletes with inferior swimming ability would require a greater energy expenditure in the swimming stage of a triathlon when a wetsuit is not able to be used. It is possible that the increased energy requirement will result in a decrease in performance during the subsequent cycling and running stages of the event.

2.1.2 Technical Efficiency and Co-Ordination in Swimming

Elite swimmers are known to be more efficient than elite triathletes.[20] The energy cost during the front crawl of pure swimmers is 21 to 29% lower, and propelling efficiency 36.4% higher when compared with triathletes.[5,20] Stroke rate is similar in swimmers and triathletes but distance per stroke (D_s) is better in swimmers at the same relative velocity reflecting greater exercise efficiency.[5,20] Although swimmers are taller than triathletes,[21] the increased D_s in swimmers is related not to their size, but to a more efficient catch during the propulsive phase of the swimming stroke.[22] Millet et al.[22] have shown that the D_s-to-height ratio in swimmers is much greater than in triathletes. D_s is

more related to performance than stroke rate and positively correlated to propelling efficiency.[20,23,24] Therefore, an increase in D_s is a good indicator of the technical improvement of triathletes in swimming.

As swimming velocity increases, the duration of the entry phase during front crawl is decreased and the pull-push phase is increased, leading to a progressive change from catch-up co-ordination to superposition co-ordination. This change leads to longer propulsive forces to overcome drag forces. Both triathletes and swimmers perform such technique modifications at velocities ranging between 80 and 98% of maximal velocity. Nevertheless, during swimming at near maximal velocity over 15m, swimmers tend to increase propulsive force, whilst in triathletes this is reduced, showing poor technical adaptation.[22] Thus, technical efficiency at high velocity may be important for performance in mass swim starts where triathletes must avoid slower athletes, as well as modifying their position when drafting behind a leading or slightly faster swimmer.

2.1.3 Drafting During Swimming in Triathlons

The opportunity to draft behind or to the side of other swimmers makes triathlon swimming unique from competitive, lane-based, pool swimming. The depression made in the water by a leading swimmer decreases the passive drag of the following swimmers by 10 to 26%.[25-27] Blood lactate concentration and rating of perceived exertion (RPE) are also reduced by 31 and 21%, respectively, in a drafting situation, possibly indicating reduced exercise stress.[28] Drafting during swimming also leads to 5 to 10% decrease in oxygen uptake ($\dot{V}O_2$) at submaximal and maximal velocities, reflecting greater economy.[19,26,28] Performance improvements of between 3.2 and 6% have also been shown to occur in drafting swimmers.[19,25] Such performance improvements range from 9 to 12 seconds over 400m, and are increased in leaner athletes.[25] However, during a 400m swimming trial the velocity is much greater than in events ranging from 1500 to 3800m, as in the Ironman triathlon event. Therefore, the drafting effect may not be as pronounced in these trials when the velocity is typically lower. That aside, it is likely that drafting behind a lead swimmer improves swimming economy through modification of stroke parameters such as stroke rate and D_s.[26] D_s is increased, probably because of a longer entry phase in combination with decreased frontal resistance. At the same time, stroke rate has been shown to be unchanged. Thus, these adaptations in combination with reduced oxygen cost indicate greater efficiency.

Anecdotal evidence suggests that better triathletes complete the first 400m of the swim stage of a triathlon distance event using a 6-beat kick at a velocity higher than the overall average speed. This is done to establish a good position in the swim field. In the middle and latter stages of the swim stage, a slower 2-beat kick may be used for the remainder of the swim resulting in less lower limb movement. There is no evidence to suggest that a change in kicking frequency during swimming will influence the metabolic responses during subsequent cycling activity. Future studies should examine whether different kicking frequencies used during swimming will influence subsequent cycling performance in a triathlon.

Preliminary data suggest there is no obvious advantage to drafting behind an athlete with a 2-beat rather than a 6-beat kick, even if passive drag is lower behind the 2-beat kick swimmer.[27] However, the distance between a 'draftee' and a leading swimmer can differ widely in triathletes (between 14 and 85cm).[27] A significant relationship ($r = -0.82$) exists between this distance and passive drag.[27] Thus, the closer the hand of the draftee to the feet of the lead swimmer, the higher the passive drag. Therefore, there seems to be a compromise between the distance from a leading swimmer chosen by another competitor, and the reduction of drag that is encountered during drafting.[27]

2.1.4 The Effects of Swimming on Cycling Performance

Prolonged swimming requires use of predominantly the upper body muscle groups. This results

in blood pooling in the upper extremities.[29] The swimming stage of a triathlon has also been shown to elicit a higher blood lactate concentration relative to the proceeding cycle and running stages.[30] Therefore, the elevated blood lactate concentration may be indicative of greater exercise stress. This combined with excessive blood pooling in the upper extremities, at the end of the swim stage may affect performance during the proceeding cycle stage. The physiological effects of swimming on subsequent cycling exercise have been examined by two research groups.[31,32]

Kreider et al.[31] found that 800m of submaximal swimming before 75 minutes of cycling at 75% of maximal oxygen uptake ($\dot{V}O_{2max}$) resulted in a significant reduction in power output (191 *vs* 159W) when compared with a control 75-minute cycle without prior swimming. $\dot{V}O_2$ (L/min) was also significantly reduced. The data from Kreider et al.[31] indicate that cycling economy, that is, $\dot{V}O_2$ relative to power output, was not affected by prior swimming. In more recent studies, Laursen et al.[32] found that 3000m of swimming at a self-selected intensity resulted in no significant differences in the average power output sustained over a 3-hour cycle time trial that followed the swim compared with control conditions without prior swimming (212 *vs* 222W). However, power output during the initial stages of the cycling trial was lower after swimming than in the control condition. The studies by Kreider et al.[31] and Laursen et al.[32] are different because of the test type (set workload *vs* time trial) and also the distance completed in the cycling trials. The reduction in power output following swimming observed by Laursen et al.[32] is likely to be detrimental to athletes' performance in elite standard-distance triathlons. The power output generated by elite triathletes is typically higher in the early stages of the 40km distance (figure 1 and table IV). An ability to generate high power outputs in the early stages of the cycle stage may be necessary for a trailing athlete to catch up with a leading group of athletes or to attempt to break clear of the leading group. However, during a longer

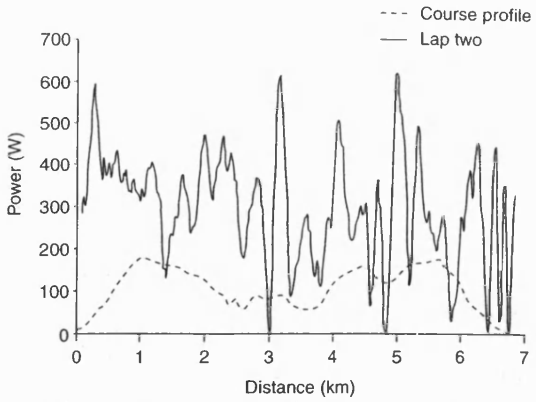

Fig. 1. An example of the power output generated by an athlete during one section (lap 2, 7km) of the cycle stage of an elite triathlon distance event (International Triathlon Union World Cup, Sydney, 2000).

distance race the effect may not be as significant because the power output required in the early stages of the cycle leg might be lower. That aside, limiting the negative effects of swimming activity on cycling power output may be particularly important in draft-legal events as it would provide a means of establishing a good position and maintaining contact with the leading cyclists.

The 3.8km swim completed by athletes in the Ironman event is a significantly longer exercise stress than that completed during the standard-distance triathlon. It is possible that differences in the duration and intensity of the swimming activity may result in different effects on cycling performance during a triathlon event. The existing data also indicate that wearing a wetsuit during the swimming stage combined with the effect of swimming behind another athlete (drafting) may result in a reduction in exercise intensity at the same relative swimming velocity.[15,26] It is likely that the physiological response during the acute phase of the cycle stage of a triathlon may be influenced by these factors. However, other researchers have shown a greater metabolic response, as evidenced by elevated blood ammonia levels, following swimming compared with the remaining cycling and running stages.[33] Therefore, the athletes' homeostatic re-

sponse to swimming together with any residual fatigue effects directly influencing lower limb function following the preceding swimming bout may also be significant.

2.2 Cycling

2.2.1 Drafting During Cycling in Triathlons

In cycling events the energy expenditure and forward motion are linked to the effects of gravity and frontal (air) resistance.[34] These are in turn influenced by the projected frontal area as well as the body mass of a cyclist in combination with the geographical nature of the cycling course.[35] Frontal resistance and consequently, energy expenditure, is reduced by drafting behind another cyclist or a group of cyclists. The extent to which this occurs is likely to be influenced by the physical characteristics of the athletes and the biomechanical characteristics of the bicycles they are using. However, the potential energy saving has implications for athletes competing in draft-legal triathlon events.

It has been shown that drafting during the cycle stage of a simulated triathlon results in a significant metabolic saving with the potential to influence the subsequent run.[36,37] Hausswirth et al.[36] found that $\dot{V}O_2$, pulmonary ventilation ($\dot{V}E$), heart rate (HR) and blood lactate concentration were all lower during 20km of cycling in a drafting position than in cycling alone at the same absolute speed. Subsequent running performance and $\dot{V}O_2$ during the run were also significantly elevated after a drafting cycle stage. More recently, Hausswirth et al.[37] established that the metabolic cost of alternating cycling in front of and behind a cyclist (in a draft position) was much higher than when triathletes drafted continuously. These authors also reported a subsequent reduction in both running performance and $\dot{V}O_2$ following cycling using a strategy of alternate leading and drafting. These two studies[36,37] are significant in that they attempt to quantify the specific metabolic demands of elite triathlon racing. At the same time they are able to establish that the metabolic cost in cycling in a triathlon is related to subsequent and self-paced running performance after cycling. More importantly, the data seem to indicate that the $\dot{V}O_2$ that is maintained during the running stage of a triathlon is influenced by the metabolic demand of the preceding cycle. Therefore, reducing the metabolic effects (and the residual skeletal muscle fatigue) of the cycling stage by drafting may result in improved running performance by way of increasing the average sustained percentage of $\dot{V}O_{2max}$ in the running stage.

Drafting 0.2 to 0.5m behind a lead cyclist at 39.5 km/h during the cycle section of a sprint triathlon has been shown to result in a lower oxygen cost and decreased metabolic demand.[36] It has also been shown that cycling behind a pack of eight riders results in a much larger decrease in energy cost than does drafting behind one, two or four riders.[38] In this study, $\dot{V}O_2$, $\dot{V}E$, HR and blood

Table IV. Power output, pedalling frequency[a] and freewheel duration data collected for a male triathlete during six laps of the cycle stage of a 2000 elite World Cup race (Sydney, Australia)

Lap number	1	2	3	4	5	6
Average power (W)	282	300	233	231	267	266
Maximum power (W)	710	675	696	679	695	689
SD	153	159	174	172	152	161
CV	54	53	75	74	57	60
Average pedalling frequency (rpm)	76	76	65	66	71	70
Freewheel duration (sec)	71	60	117	97	85	82
Maximum pedalling frequency (rpm)	122	117	119	146	125	111

a Power output values represent 5 sec averages. The minimum pedalling frequency and power output for each lap represented 0 rpm and 0W, respectively.

CV = coefficient of variation; **SD** = standard deviation.

lactate concentration. were all lower in a drafting situation. Thus, the existing data demonstrate that participating in triathlons involving a draft-legal cycle stage results in a considerable energy saving. The obvious benefits of the decrease in energy expenditure at a given velocity in draft-legal triathlons are the ability to cycle at a higher velocity at the same relative exercise intensity. At the same time, weaker cyclists (in a draft-illegal situation) may be able to maintain better overall position, which may be tactically positive when the running stage is completed. Furthermore, subsequent running performance is improved because of maintenance of a higher percentage $\dot{V}O_{2max}$.

2.2.2 Physiological Demands of Time-Trial- and Criterion-Based Cycle Courses

Exercise intensity is known to be relatively constant during competition cycling time trials.[39] Cycling time trials are usually completed on relatively flat courses and under non-drafting conditions. To better accommodate the needs of the viewing public, the cycle stage of elite World Championship or World Cup level standard-distance triathlons is commonly completed over multiple laps. Race organisers may include one or several hill sections within each loop of the course, in an attempt to break up groups of drafting athletes and thereby increase the interest of the event. Therefore, in contrast to individual time trials, the race demands of elite standard-distance competition may consequently be more similar to that of cycle criterion races, where rapid accelerations result in supra-maximal power outputs interspersed with periods of submaximal exercise.

The inclusion of hills or more 'technical' bike courses may change the physiological demands during draft-legal competitions. Smith et al.[40] examined the power output during the cycle stage of an ITU triathlon event using the SRM crank system enabling work output to be quantified. They concluded that power output fluctuated markedly during the cycle stage with athletes generating between zero to well in excess of the maximal levels.

The metabolic effects of varying power output from submaximal to supra-maximal intensities have been examined during cycle exercise.[41,42] Liedl et al.[41] found that in comparison to a steady-state cycle ride at 100% of the intensity sustained during a 60-minute time-trial intensity there were no significant physiological differences when a similar ride was completed when 5-minute efforts at 105% were interspersed with efforts at 95%. This study[41] demonstrated no significant physiological effects of work outputs incorporating variable power fluctuations. However, it is likely that an exercise protocol involving more supra-maximal efforts (>$\dot{V}O_{2max}$) may induce significantly greater metabolic or neurological fatigue resulting in a greater performance decrement compared with a steady-state cycling trial.

There have been two studies[42,43] to date that have examined the physiological effects of an exercise protocol involving 'stochastic' power output on subsequent submaximal exercise performance (as in a triathlon event). Palmer et al.[42] had a group of well trained cyclists perform 150 minutes of cycling involving periods of higher intensity exercise (~80% of maximum workload obtained from an incremental exercise test) with more submaximal exercise. Following the 150-minute exercise protocol a 20km time trial was performed. This was compared with another trial involving a 20km time trial performed after 150 minutes of steady-state submaximal exercise. The results demonstrated that time-trial performance was reduced following the stochastic trial. In a second study,[43] the same research group found that total muscle glycogen depletion, depletion in type II fibres and total glucose oxidation were greater following a similar bout of 'variable intensity' exercise compared with a steady-state ride of 140 minutes. Despite these findings, subsequent 20km cycle time-trial performance remained similar between the two trials. Therefore, it is likely that the heightened glycogen depletion, especially in fast-twitch muscle fibres, following a period of stochastic power output compared with an exercise protocol of lower intensity exercise,

may not affect subsequent time-trial performance. However, other studies using a cycle exercise protocol of <60 minutes interspersed with more supramaximal efforts followed by a similar performance trial may induce more pronounced decrements.

The effects of variable power output on subsequent running performance have only recently been examined.[44] In this study, investigators found that varying the intensity by between 20 to 40% of the average power output during a 60-minute time trial had no effect on performance during a subsequent 10km run compared with a steady-state cycling bout. However, the participants were relatively untrained ($\dot{V}O_{2max}$ = 53 ± 6 ml/kg/min). At the same time, it is likely that a protocol involving more supra-maximal efforts interspersed with submaximal exercise, as quantified by Smith et al.,[40] may induce a significant performance decrement and metabolic change during submaximal running activity.

The influence of physical characteristics on cycling and running performance has been previously documented.[35,45] It was suggested that during time trials, larger cyclists are usually more successful compared with smaller cyclists because in flat terrain competitions the only force inhibiting forward motion is that of air resistance.[46] Indeed, a significant correlation ($r = 0.94$; $p < 0.01$) has been reported between 40km cycle time-trial performance and body mass scaled (0.32) to evaluate level ground cycling ability.[35] During cycle races where a greater portion of the race is composed of hills, smaller cyclists are more successful because they have a lower body mass, and therefore resistance to gravitational force will be less in these individuals. It has been recently reported that in well trained cyclists the body mass is significantly lower in specialist 'climbers' compared with flat terrain specialists (60 to 65kg *vs* 70 to 75kg).[47] The body mass of elite male triathletes has been reported to range between 65 and 75kg.[21,48] Thus, it is possible that smaller triathletes may perform better over courses involving a draft-legal undulating cycle course because of a lower gravitational force to overcome during both the cycle and running stage. In contrast, larger athletes may excel in flatter, non-drafting cycle courses. This has obvious implications for talent identification and selection of triathletes with similar $\dot{V}O_{2max}$, but different physical characteristics, who are competing in draft-legal races or in races that involve hill sections within the cycle stage. At the same time, distinguishing the most optimal physical characteristics for a particular cycling course may not necessarily result in improved performance in a triathlon overall, possibly because of the influence of contrasting physical characteristics and running performance especially when running exercise is performed after cycling.

Lucia et al.[46] have reported that an elevated $\dot{V}O_{2max}$ and improved buffer capacity may be important attributes for performance during cycling competitions that involve repeated bouts of exercise approaching or exceeding $\dot{V}O_{2max}$. Therefore, these attributes may also equate to improved performance in draft-legal triathlon races on flat and technical courses where there is a demand for rapid acceleration followed by the necessity to recover quickly.

2.2.3 Pedalling Frequency During Cycling in Triathlons

The pedalling cadence (PC) [rpm] used by athletes during the cycle stage of a triathlon is relatively unknown. However, empirical observations (e.g. Table IV) at the highest level show great variability in PC (range 0 rpm– free wheel – to >120 rpm) in draft-legal races. Most studies[49-52] examining PC at different exercise intensities clearly demonstrated the metabolically optimal PC is between 60 to 80 rpm. However, other researchers[36] have shown that the PC is higher than this value during a simulated triathlon. At the same time, the PC is higher (~90 *vs* 100 rpm) in a drafting situation where the exercise intensity is also reduced compared with cycling alone.[36]

Whilst some research groups have investigated the PC that elicits the lowest metabolic response,[49-52] other authors suggest that a bio-

mechanically optimal PC exists at ~90 rpm where neuromuscular recruitment [as determined by electromyogram (EMG) measurements] is lowest during submaximal exercise.[53-55] Recently, it has been shown that the freely chosen PC in triathletes (~90 rpm) during submaximal exercise is close to the suggested biomechanically optimal cadence.[56,57] This PC is close to the freely chosen cadence used in elite cycling during flat stages (89 rpm) or time trials (92 rpm).[58] Typically, during prolonged cycling exercise a decrease in freely selected PC occurs.[36,59] It has been shown that during submaximal exercise the PC of triathletes is reduced to 83 rpm, whereas elite cyclists are able to maintain close to 90 rpm for over several hours.[52,58] Thus, it is possible that maintenance of PC close to an optimal level without decrement may be associated with improved cycling performance in athletes within similar aerobic capacity. However, the mechanisms surrounding these adaptations are not well understood and may, in part, be caused by the differences and modes of training performed by cyclists and triathletes.

2.3 Running

2.3.1 Effects of Cycling on Running Performance

Some authors[60] have concluded that the ability to optimally link each discipline is important for successful triathlon performance. Several authors have examined the physiological stress that occurs during each segment of a triathlon race linked together in comparison to each stage performed alone.[31,61] Whilst there is some evidence that cycling performance and associated metabolism are affected by prior swimming,[31,32] a more dramatic effect appears to be related to running after cycling. Most research in this area has therefore examined the physiological effects of cycling on subsequent running performance. Some such studies,[62] however, were conducted in participants that were not triathletes and in conditions that did not adequately simulate the environment of competitive triathlons.

The first study to directly examine the effects of prior cycling (and indeed swimming) on subsequent running performance was conducted by Kreider et al.[31] Nine moderately trained triathletes performed a simulated triathlon comprising a 0.8km swim, a 40km cycle and a 10km run. On another occasion, each participant performed separate cycle and run stages without prior exercise. It was shown that $\dot{V}O_2$ and $\dot{V}E$ were elevated during the 10km run after swimming and cycling compared with the single run without prior exercise. Significant increases in HR, and reductions in arterial blood pressure and stroke volume indicating a reduction in blood volume that may have been caused by dehydration, also occurred within the running stage. An elevated core temperature evident during the triathlon run may have also contributed to the increase in metabolic demand. Other studies[36,61,63,64] have also shown an increased $\dot{V}O_2$ relative to work output, or decreased running velocity after a bout of cycle exercise compared with running without preceding exercise.

The most confounding methodological problem in the literature examining the effects of cycling on running is variation in exercise protocols. Some researchers[61,63] have had participants run at a set speed corresponding to a perceived race effort on two occasions and imposed cycling exercise before one such bout. Other researchers[31,36] have allowed participants to run at a self-selected pace after cycling. The physiological difference between these protocols is that when a participant is under simulated race conditions, they are allowed to vary their running speed. It is possible that an intermittent race strategy often referred to as 'surging' may be beneficial when running after cycling. That aside, the different exercise protocols may influence the metabolic response observed and make conclusions regarding the mechanism of reduced performance when running after cycling difficult to establish.

Some authors suggest that an increase in fatty acid utilisation associated with glycogen depletion is evident during running in a triathlon race and this would explain the higher $\dot{V}O_2$ values observed.[61] However, reported respiratory quotient (RQ) val-

ues >0.95 indicate that there is still a substantial contribution of carbohydrate-related sources as in other exercise bouts >80% $\dot{V}O_{2max}$.[65] Furthermore, other studies have shown that during prolonged running there is a decrease in RQ that is not associated with an increase in the energy cost of exercise.[66] Therefore, it is likely that changes in exercise efficiency with neuromuscular fatigue may be relevant to the contrasting metabolic responses observed when running after cycling as opposed to running without previous activity.

Cycling exercise is predominantly concentric in contrast to running, which involves largely eccentric muscle contractions. Differences in motor unit recruitment patterns also exist between the two exercise modes.[67] Therefore, it is possible that the observed changes in exercise metabolism when running after cycling may be caused by a change in running mechanics or recruitment patterns as a consequence of the previous contrasting activity. To date, studies[61,67,68] have attempted to examine the effects of cycling on running biomechanics, but not on motor unit recruitment patterns, during running after cycling activity. Quigley and Richards[67] found no significant biomechanical changes during 30 minutes of running after 30 minutes of cycling in triathletes. Hue et al.[61] found no significant change in stride length or frequency during a 10km run after a 40km cycling bout. Millet et al.[68] extended these findings by using a device that was able to quantify the kinetics of the lower limbs and thus, the mechanical cost of running after cycling. They concluded that the tendency for a reduction in the mechanical cost of running after cycling in more elite triathletes may be caused by better regulation of muscle stiffness. The current literature therefore suggests prior cycling does not affect running biomechanics. However, it is possible that muscle stiffness regulation during running after cycling may be influential and hence this effect could explain the change in exercise metabolism during running in a triathlon. At the same time, the data presented so far concerning the changes in gait during running after cycling have used a variety of methodological approaches. Thus, it is possible that the technique used to measure the biomechanical changes during running may influence the results and conclusions drawn from these studies.

Some research[59,69,70] has quantified motor unit recruitment patterns using EMG during prolonged cycling and running exercise. Other studies[70] have reported that decreased running velocity is associated with changes in EMG patterns and fatigue during a 10km race. It is likely that these adaptations are evident and even pronounced during running after cycling compared with running alone.

As with swimming during a triathlon, there is considerable variation in event distance and duration. It is likely that a change in exercise intensity or duration during the cycle stage will affect exercise metabolism and performance during subsequent running activity of similar variation in intensity and duration.

2.3.2 Effect of Pedalling Frequency During Cycling on Subsequent Triathlon Running

The effect of the PC used in the cycle stage of standard-distance triathlons on the subsequent run is unclear. Hausswirth et al.[36] showed that cycling in a drafting position led to a 6.3% decrease in freely chosen PC over that exhibited in a non-drafting position at the same power output. Typically, reducing the PC at a given work rate leads to an increase in force application to the pedals during submaximal exercise of the same relative intensity.[71] This, in turn, may influence muscle recruitment patterns and fatigue responses during prolonged exercise.[59] Therefore, it is possible that modifying the freely selected PC may affect subsequent running performance.

Vercruyssen et al.[72] has shown PC during a 30-minute cycle at 73.6 ± 3.6% $\dot{V}O_{2max}$ that resulted in the most economical response during a subsequent 15-minute submaximal run was closer to the metabolically optimum cadence (72.5 ± 4.6 rpm) rather than to the theoretical biomechanically optimal cadence of 90 rpm.[53-55] Both the (higher) mechanical optimum cadence and the freely cho-

stronger runners. Thus, it is possible that a threshold level of metabolic or neurological fatigue during the cycle stage exists and that this may influence subsequent running performance in triathletes with varying ability with regard to pure running. At the same time, the duration required for complete adjustment to the change from cycling to running, and the effect of this on running mechanics and economy, is probably specific to the individual.

3. Conclusion

This review has outlined some technical aspects of the triathlon that are relevant in age- group and elite competitions. The relative impact on performance of some of these technical factors make triathlons unique from endurance swimming, cycling and running. Practising exercise physiologists recommend performance and physiological diagnostic testing for triathletes in the individual sports of swimming, cycling and running. This is done for the purposes of monitoring training-induced adaptations and performance modelling. Specific factors within a triathlon competition may influence performance in each sport within a triathlon and, more especially, influence overall race performance. Thus, considerations and approaches should be made to compensate for these factors so that performance diagnostics and endurance practice are specific to the different triathlon events.

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Appendix 2. An example of a general information sheet (Experiment Four)

SUBJECT INFORMATION SHEET

A research study examining the lactate threshold and endurance exercise in cyclists and triathletes.

November 2001

You are invited to participate in a research study concerning the significance of the lactate threshold during endurance exercise. Below is some information to help you decide whether or not you would like to take part.

Background and purpose to the study
During exercise lactate is continually being produced but also eliminated from the blood stream. When the intensity of exercise is gradually increased from rest, there is a point when blood lactate rises dramatically above resting levels. The point where blood lactate rises is known as the lactate threshold. During exercise oxygen is necessary for the body to continue to exercise. The rate of oxygen consumed at the point of the lactate threshold (LT) together with the maximal possible rate of oxygen consumption ($\dot{V}O_2max$) is important in analysing the conditioning status of endurance athletes.

This research study aims to examine how different incremental exercise protocols effects the LT in trained cyclists. At the same time, the study is looking to examine the significance of some key variables obtained from an incremental exercise test and how they correlate with 30 min (short) time trial performance.

Why have I been invited as a subject?
You have invited to participate in this study because you compete in cycling or triathlon. You are also male and aged between 18 and 40 years. We have also selected you because you will have trained and competed in cycling time trials long enough to appreciate the physiological demands of this activity.

How many days and for long are you required on each day?
You will be required to attend the exercise physiology laboratory, Department of Sport and Exercise Science, Bath University on four occasions over a one to two-week period. The sessions will be approximately 60 min in length. Each session will be scheduled according to your schedule and commitments. The four test sessions will include-

(1) Incremental exercise test – this involves a progressive increase in workload (intensity) every 60 s until fatigue. We will measure peak minute power output and maximal oxygen uptake ($\dot{V}O_2max$)
(2) Lactate test One – this will involve a continuous incremental test (9 x 3 min progressive work bouts). The first 3 min effort will be at 50% of maximum with

each 3 min effort increased by 5% until fatigue is reached. At the end of each 3 min effort blood lactate will be measured by obtaining a small amount of blood from your earlobe.

(3) Lactate test Two – as for lactate test one except that each stage will be 5 min in duration as opposed to 3 min.

(4) 30 min TT i.e. ride as fast as you can in 30 min.

For each test you will exercise on an SRM cycle ergometer. This is the most modern cycle ergometer available and closely matches cycling on your own bike. You should bring clipless pedals and cycling attire. No helmet is necessary. You should also bring your own bike on the first occasion so that measurements can be made of your bike set up. The SRM ergometer can be adjusted to exactly your own bike dimensions.

How do I prepare for each test session?

With the exception of the 30 min TT (Test Four), during the 2-3 hours prior to each test you should NOT eat or drink caffeine, but rest for the test. It is OK to consume water. Bring along food and sports drink for after the test. In the period (6-2 hrs) prior to each incremental test (Test 1-3) you should eat regular quantities of carbohydrate foods or drinks.

A high carbohydrate drink will be supplied to you just prior to the 30 min TT.

During the two weeks of testing we encourage you to continue with your daily training. However, 24-hrs prior to each test you should follow the recommendations listed below

(1) No demanding high intensity exercise

(2) Continue to maintain the diet you are accustomed to but adhere to a high carbohydrate meal 2-3 hours prior to tests 1-3.

(3) No food or caffeine to be consumed prior to tests 1-3.

Disadvantages, risks and benefits

During the testing you will be required to exert yourself as maximally as possible during strenuous cycling activity. You will also have a small amount of blood taken from the earlobe at regular stages during tests 2, 3 and 4. This is a standard procedure and causes little discomfort. The risk of infection during the blood sampling is also minimal. The utmost care will also be taken during the blood sampling procedure and sterilised equipment will be used to obtain blood at all times.

Whether or not you agree to take part in this study, where ever possible you will be advised on your training program. You will also be provided with a report detailing the results of the testing ($\dot{V}O_2max$, LT etc) and some recommendations for training. At the same time you will have the option to complete an additional lactate test (Test 2) at a time of your request. In this way you will be able to compare the results of the first tests you complete with an additional test. All

information obtained from the testing will be confidential. It is likely the results of this study will be published but your name or any information that allows your identification will not appear on these reports.

The data collected from this research will form part of a PhD thesis. Your participation in this investigation is most appreciated and is entirely voluntary. However, you are free to withdrawal from the study at any stage.

Further details
Further information can be obtained from Mr David Bentley on 01225 826 696 or email [sppdjb@bath.ac.uk]

Appendix 3. The pre-activity questionnaire used in each of the four experiments.

Medical screening questionnaire

This form is used as a pre-participation health and risk factor screening device and should be completed **prior to the commencement of an exercise test.**

The information obtained in this medical assessment will be kept as **CONFIDENTIAL.** Only the staff member related to the exercise test may access to the information.

Client's Surname (Mr., Mrs., Ms.): _____

Given Names: _____

Date of Birth: _____

Address: _____

_____ Postcode: _____

Contact Telephone: _____ (Home) _____ (Work)

(1) FAMILY MEDICAL HISTORY.
Has any near relative brother (B), sister (S), father (F), mother (M), grandparents (GP) suffered:

Please tick the appropriate column

	No	Yes	Relation	Age	Remarks /Details
Apoplexy (stroke)					
Congenital heart trouble					
Rheumatic heart disease					
Heart operation					
Angina					
Heart attack					
Sudden death					
High blood pressure					
High cholesterol					
'Hardening of arteries'					
Asthma					
Lung disorder					
Bronchitis, emphysema					
Hay fever					
Diabetes					
Gout					
Arthritis					
Epilepsy					

(2) PAST MEDICAL HISTORY

Have you suffered any of the following conditions at any time:
(Please tick the appropriate column)

	No	Yes	Details
Rheumatic or scarlet fever			
Heart trouble or murmur			
Heart palpitation			
High blood pressure			
Heart attack			
Chest pain/Angina			
Stroke			
Disease of arteries or veins			
Undue limiting shortness of breath with exercise			
Fainting or blackout			
Loss of consciousness or fainting with exercise			
Epilepsy			
Lung or bronchial disease			
Asthma			
Hay fever			
Anaemia			
Diabetes			
Thyroid disease			
Arthritis, rheumatism or gout spondylitis, disc trouble or back injury			
Serious accident or injury			
Surgical operation			
Congenital abnormality			
Other serious illness (or conditions that may affect exercise)			
For female only: Having normal/regular periods			

(3) PRESENT MEDICAL CONDITION

Are you currently suffering or have you in the recent past suffered any of the following conditions (Please tick the appropriate column):

	Immediately prior to the test	
	Yes	No
Cough		
Stuffy nose or sore throat		
Tonsillitis, glandular fever		
Hepatitis		
Diarrhoea/vomiting		
Headaches		
Shortness of breath		
Pain in chest, left arm or neck at rest, or during physical activities		
Heart palpitations		
Cramp in legs		
Abnormal loss of blood		
Insomnia		
Indigestion of constipation		
Swollen, stiff or painful joints		
Backache		
Sports injury or other injury		
Other symptom or illness, or surgery		
Any deterioration in training or competitive performance		
Any other conditions that may contraindicate to exercise or affect exercise capacity		
For female only: Currently in pregnancy		
If yes, provide details		

(4) CURRENT MEDICATION

This section should also be checked **IMMEDIATELY PRIOR TO THE EXERCISE TEST.**

State the name and dosage of any drugs or medicines that you are taking regularly:

Drug	Dose	Time of last dose

Appendix 4. An example of an informed consent document (Experiment Four)

CONSENT FORM

Metabolic responses to endurance exercise in cyclists with high or low lactate threshold

Mr David Bentley

The Department of Sport and Exercise Science, Bath University

Please initial box

1. I confirm that I have read and understand the information sheet dated..... (version .....) for the above study ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time..... ☐
3. Any information obtained from this investigation will be supplied to me and strict confidentiality will be maintained to others except by my request. ☐
4. I agree to take part in the above study. ☐

Name of subject	Date	Signature
Name of person taking consent (if different from researcher)	Date	Signature
Researcher	Date	Signature

Appendix 5. Nutritional guidelines administered to each subject prior to each time trial and set workload trial (Experiments Three and Four).

How do I prepare for each test session?

General

During the two-week period when you will be tested you should continue with your daily training. However, generally speaking 24-hrs prior to each test you should follow the recommendations listed below
No demanding high intensity exercise
Continue to maintain the diet you are accustomed to but adhere to a high carbohydrate meal 2-3 hours prior to tests 1-3.
No food or caffeine to be consumed prior to tests 1-3.
Complete a diary record of your food intake.

Test One: VO2max Test

2-3 hours prior to the test session you should have a meal consisting of high carbohydrate foods. During the 2-3 hours prior to each test you should NOT eat or drink caffeine, but rest for the test. It is OK to consume water. In fact, do drink water at 250ml-300ml every 30-60min. In other words stay well hydrated. Bring along food and sports drink for after the test.

Test Two: Lactate Test

As for test one

Test Three: 20-min trial

The test will be quite demanding, but very achievable if you prepare as if you would for a race (without taper). You should not have completed any strenuous activity in the 24-48hrs prior to the test. It is OK to do a bike of <60-min duration at a very low intensity on the morning the test. Swimming is OK at any stage. Running should not be completed in the 24hrs prior to the test.

You should attend the exercise physiology laboratory after an overnight fast. That is, you should not have eaten on the morning of the test. That means, nothing-sorry. You are allowed to drink water at anytime and this is recommended at 250ml every hour before the test. You will be supplied with a carbohydrate drink before the test and at regular intervals throughout the test so don't worry about depletion of energy or starvation.

On the day before the test you should consume 3 good meals high in carbohydrates. It is most important that you 'fill up' on quality foods the night before the test. It is a good idea to eat a big meal about 6-7pm than have a snack just prior to going to bed.

You will be required to complete a record of food intake in the 24-hrs prior to the test so that you can refer to this in the period prior to the 90-min trial and consume a similar diet.

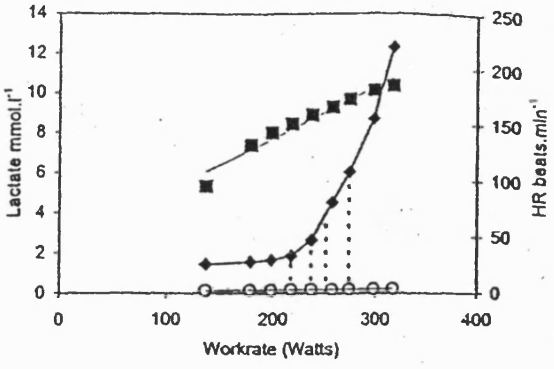
It is important to treat this trial like a race (without disrupting your winter training). Therefore, stay well hydrated the day before (250ml/hr of water or CHO drink). Eat small meals regularly ie fruit, pasta, rice, bread, muffins, sports bars. If all this is done, the sessions will be excellent training for you and not a struggle. In many respects, the trials are about appropriate nutrition rather than fitness.

Test Four 90-min trial
As for the 20-min trial

Questions
David Bentley 01225 826696 Email sppdjb@bath.ac.uk

Appendix 6. An example of the excel worksheet used to calculate the lactate threshold and onset of blood lactate accumulation in each experiment.

	Watts	VO_2	[La]	HR
1	136	2.33	1.43	95
2	178	2.61	1.55	132
3	198	2.67	1.65	143
4	217	3.19	1.86	151
5	237	3.31	2.65	159
6	257	3.47	4.53	166
7	274	3.65	6.05	173
8	298	3.9	8.7	181
9	317	4.27	12.3	185
10				



Marker		Watts	VO_2	[La]	HR
Increase in	0.4	217	3.2	1.9	151
[Lactate] of..	1	237	3.3	2.7	159
Reference	4	251	3.4	4.0	164
[Lactate] of...	6	273	3.6	6.0	173
	Ltlog	213	3.0	1.7	144
	Ltlog	213	2.7	1.7	144
	Dmax	241	3.3	3.1	157
	Dmax	241	3.3	3.1	161

Bold = interpolated
Otherwise modelled

1 Open NEW template prior to each dataset
2 Enter Raw Data in white cells c6 to f15
3 Select Dmax sheet
4 Click Tools, Solver and Solve
5 Select LTLog sheet
6 Click Tools, Solver and Solve

* If you have ANY missing lactate data omit the entire row of data
** Missing VO_2 and HR values should be tolerated